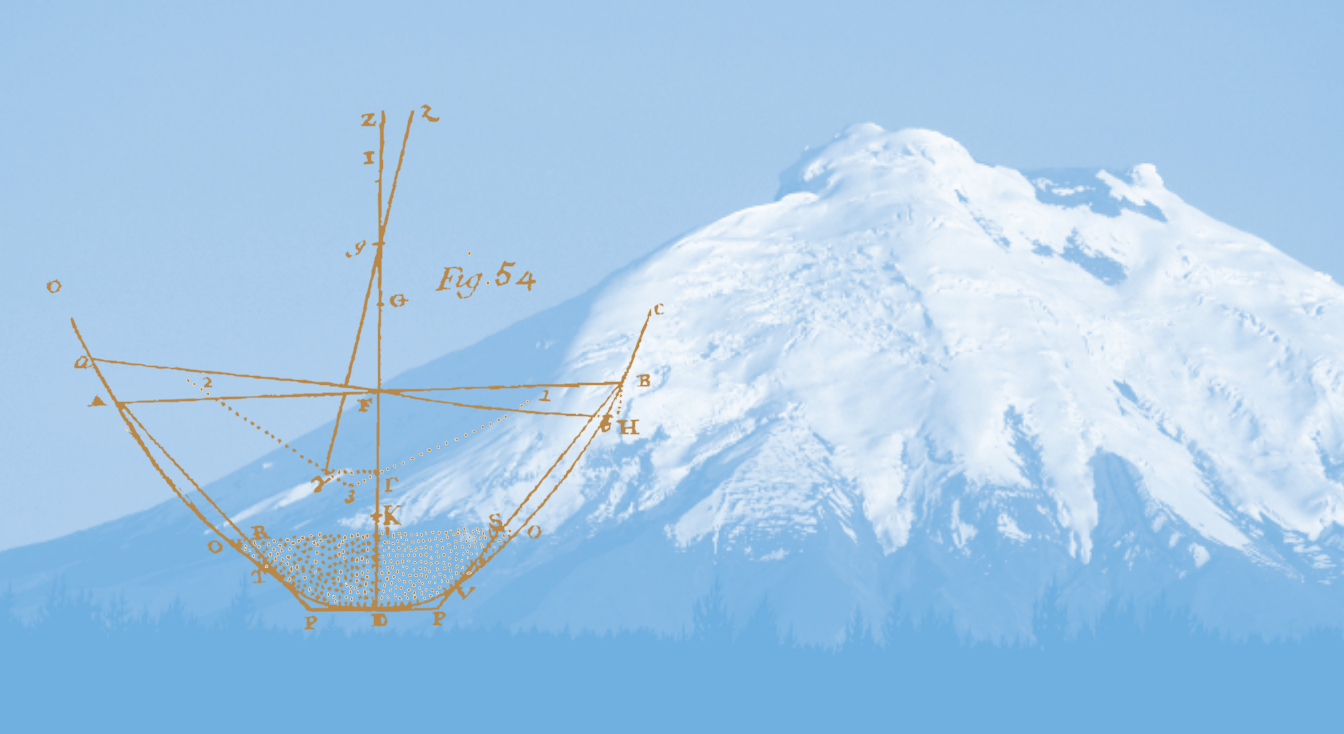
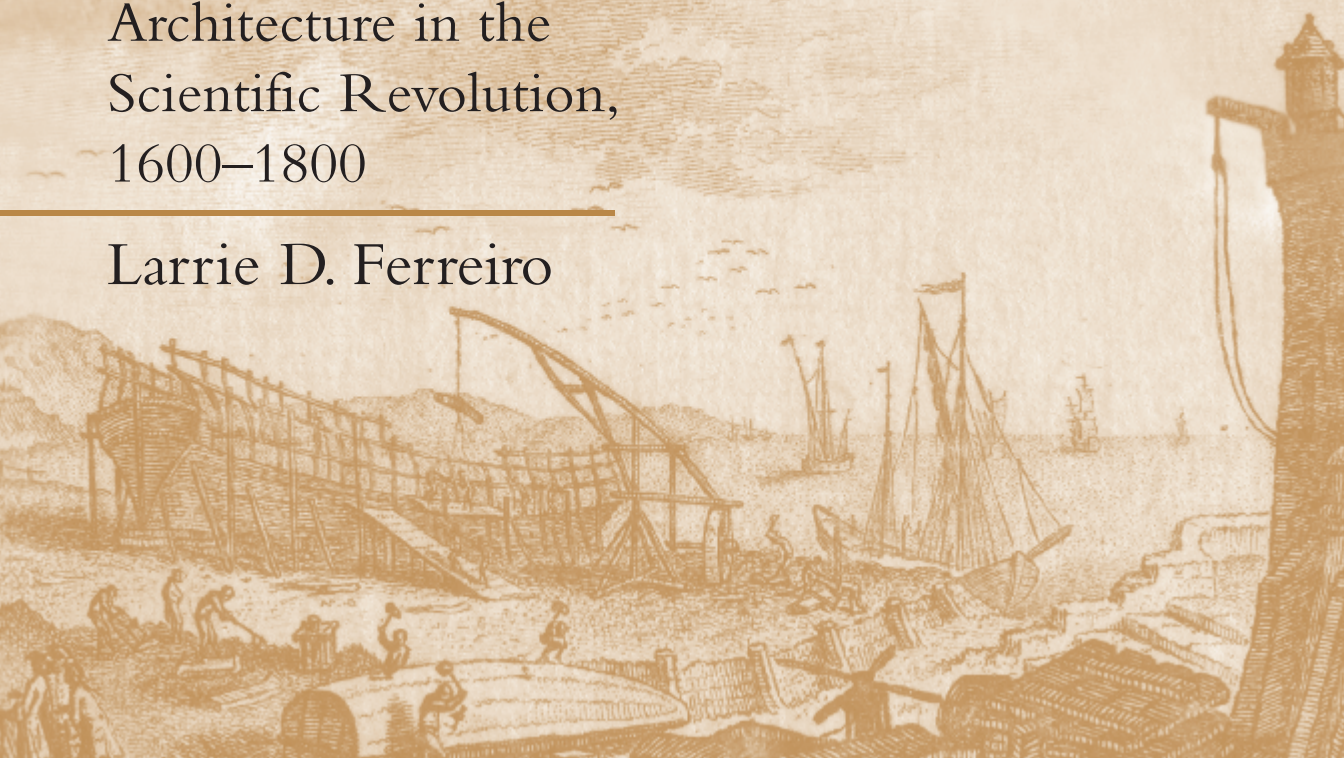




SHIPS AND SCIENCE

The Birth of Naval
Architecture in the
Scientific Revolution,
1600–1800

Larrie D. Ferreiro



VISIT...

LANZAROTE
Caliente.COM

Ships and Science

Transformations: Studies in the History of Science and Technology

Jed Z. Buchwald, general editor

Jesuit Science and the Republic of Letters

Mordechai Feingold, editor

Ships and Science: The Birth of Naval Architecture in the Scientific Revolution, 1600–1800

Larrie D. Ferreiro

Wireless: From Marconi's Black-Box to the Audion

Sungook Hong

The Path Not Taken: French Industrialization in the Age of Revolution, 1750–1830

Jeff Horn

Spectrum of Belief: Joseph von Fraunhofer and the Craft of Precision Optics

Myles Jackson

Affinity, That Elusive Dream: A Genealogy of the Chemical Revolution

Mi Gyung Kim

American Hegemony and the Postwar Reconstruction of Science in Europe

John Krige

Conserving the Enlightenment: French Military Engineering from Vauban to the Revolution

Janis Langins

Picturing Machines 1400–1700

Wolfgang Lefèvre, editor

Secrets of Nature: Astrology and Alchemy in Early Modern Europe

William R. Newman and Anthony Grafton, editors

Historia: Empiricism and Erudition in Early Modern Europe

Gianna Pomata and Nancy Siraisi, editors

Nationalizing Science: Adolphe Wurtz and the Battle for French Chemistry

Alan J. Rocke

Ships and Science

The Birth of Naval Architecture in the Scientific Revolution, 1600–1800

Larrie D. Ferreiro

**The MIT Press
Cambridge, Massachusetts
London, England**

© 2007 Massachusetts Institute of Technology

All rights reserved. No part of this book may be reproduced in any form by any electronic or mechanical means (including photocopying, recording, or information storage and retrieval) without permission in writing from the publisher.

MIT Press books may be purchased at special quantity discounts for business or sales promotional use. For information, please e-mail special_sales@mitpress.mit.edu or write to Special Sales Department, The MIT Press, 55 Hayward Street, Cambridge, MA 02142.

This book was set in Stone by SNP Best-set Typesetter Ltd., Hong Kong and was printed and bound in the United States of America.

Printed on recycled paper.

Library of Congress Cataloging-in-Publication Data

Ferreiro, Larrie D.

Ships and science : the birth of naval architecture in the scientific revolution, 1600–1800 /
Larrie D. Ferreiro.

p. cm. – (Transformations: studies in the history of science and technology)

ISBN-10: 0-262-06259-3

ISBN-13: 978-0-262-06259-6

1. Naval architecture–History–17th century. 2. Naval architecture–History–18th century.
 3. Mechanics–History–17th century. 4. Mechanics–History–18th century.
 5. Shipbuilding–History–17th century. 6. Shipbuilding–History–18th century. I. Title.
- II. Series: Transformations (MIT Press)

VM156.F47 2006

623.8'109032–dc22

2006044986

10 9 8 7 6 5 4 3 2 1

Contents

Preface	vii
Terms, Symbols, Units of Measure, and Money	xix
Acknowledgments	xxiii
Prologue	Down From the Mountain 1
Chapter 1	"Mere Carpenters" 23
Chapter 2	Deriving the <i>Dérive</i> 51
Chapter 3	A Shock to the System 113
Chapter 4	Inventing the Metacenter 187
Chapter 5	The Great Works 259
Chapter 6	Genius and Engineering 279
Epilogue	Promised Land 307
Appendix	Personages 311
Notes	323
Bibliography	377
Index	429

Preface

Rationale for This Work

The genesis of this work was a conversation I had with my then-girlfriend (now my wife), Mirna, in the summer of 1987 while on a drive in the countryside. Having recently finished my master's degree in naval architecture at University College London (where British naval constructors are educated), and back to work designing ships for the U.S. navy, I remarked to her that we naval architects use many theorems and formulas named for people we know nothing about. We learn that the Froude number, used in scaling models for towing-tank tests, was devised by the British civil engineer William Froude, who in the 1870s developed the basic theories used today to predict ship powering. But he is almost the only person known to us. In particular, I pointed out that naval architects frequently use "Bonjean curves" to quickly determine displacement and center of buoyancy at any draft. But who was Bonjean? The only reference to him is a short statement in the standard textbook *Principles of Naval Architecture*: "The diagram of Bonjean curves was first proposed at the beginning of the nineteenth century by Bonjean, a French naval engineer."¹

As I discovered 15 years later, Antoine Nicolas François Bonjean was a midlevel French naval constructor who served his country during the Napoleonic Wars, built a few ships, had one publication to his name, and retired at a very early age due to illness. He was born in Paris in 1778 and became a student engineer in 1794, during the height of the French Revolution, first as a civil engineer and then in the navy. He became a constructor in the French Corps of Maritime Engineering in 1798, serving his first years on a frigate fighting against the British in Egypt, later helping investigate Egyptian antiquities. He returned to France in 1801 after Napoleon's defeat at Alexandria, and worked in various dockyards around the country on the construction of several frigates and bomb vessels. In 1808, while he was at Lorient, he wrote and subsequently had published *Nouvelles Échelles de déplacement* (New Scales of

Displacement), which described the “Bonjean curves,” perhaps his only legacy.² In 1813 he was sent to help Frankfurt, still an ally of Napoleon, build a flotilla for the Rhine River, but suffered terribly from “famine” and an unnamed disease, and returned to France. In 1815 he was given special dispensation to retire at age 37 due to illness. There is no record of any family, and his dossier ends in 1822.³

I began with the idea of writing about unknown people such as Bonjean. The idea evolved into writing about the major developments in ships, but I soon discovered that the field was vast, including several well-researched areas in marine archaeology and naval history. Later, while working on exchange at the French Directorate of Naval Construction, (DCN), I discovered that the application of theory to ship design was still largely unexplored, even in France, where most of the early developments began. I decided to pursue my Ph.D. dissertation on that subject at the University of London’s Imperial College. I completed it in 2004, and it forms the basis for this work.⁴ In fact, this book has been 20 years in the making.

Although naval and maritime history has always included a study of ships as well as personnel, strategy, and tactics, it is only since the 1970s that a handful of naval and maritime historians around the globe have taken a critical look at the fundamental matters of ship design and construction, as well as the infrastructure of shipyards, laboratories, and personnel that supports them.⁵ However, the role of scientific theory in the development of ships is very rarely examined. During my discussions with historians around the world, I came to realize there are very few critical works on historical aspects of naval architecture in any language; the few that there are, tend to be very specific to a particular subject; and almost no major work of naval architecture has been critically evaluated.

This is not true of many other engineering disciplines. For example, the field of aeronautics is the grist for the mill for Walter Vincenti, who uses it to demonstrate how engineers work day-to-day in his book *What Engineers Know and How They Know It: Analytical Studies from Aeronautical History*. Hunter Rouse and Simon Ince’s *History of Hydraulics* provides a comprehensive, critical history of the subject and gives some context for its scientific and technological development.⁶ By contrast, there has never been, to my knowledge, a synthesis of the history of naval architecture in any language that critically evaluates the reasons for its development and application, and takes into account the exchange of ideas between individuals of different nations.

Very well: I will write the first.

I have aimed this first comprehensive work at three separate but related audiences: science and technology historians, as an analysis of a previously overlooked facet in the development of rational mechanics; naval and maritime historians, as a crucial

part of the evolution of ships; and naval architects, to help them better understand how their profession came to be. My hope is that this book will inspire further research in the history of naval architecture by a mixture of these three groups. I am aware that my book will, to some extent, shape the ideas and research for some time to come. I accept—and expect—that this further research may call into question my own assumptions and overturn many of my analyses. This work will have succeeded if it becomes the standard reference in five years' time. It will have failed if it continues to be the standard reference thirty-five years hence.

Structure of This Work

This is the first part of a two-part project describing the history of naval architecture from its beginnings until today. This first work, which is quite self-contained, covers the birth of naval architecture within the Scientific Revolution, which the science historian Alfred Rupert Hall nominally dated as lasting from 1500 to 1800.⁷ However, I set the beginning of my subject at about 1600, when the works of the Dutch engineer Simon Stevin and the French philosopher Blaise Pascal first expanded on Archimedes' fundamental theorems, which then became integrated into rational mechanics and began to play a role in the study of naval architecture. Similarly, I have chosen 1800 as a natural end point for this work, marked both by the French Revolution and the Napoleonic Wars that stifled much government-sponsored scientific research, and by the short-lived British Society for the Improvement of Naval Architecture, which heralded the development and use of ship theory by independent engineers. The second work in this project, tentatively titled *Bridging the Seas: The Development of Naval Architecture in the Industrial Age, 1800–2000*, will pick up the story at that point, and will include certain themes that had begun in the period of the first book (e.g., research into structures and strength, as well as mechanical propulsion) that were not fully developed until the advent of iron and steam.

My objective in this work is to tell the story of how and why naval architecture—, i.e., the implementation of ship theory in design—was originally developed and subsequently used by constructors. This story has many threads. For a start, much of the development of ship theory was carried out under the auspices of the navies, which were the first to make use of it in ship design and construction. However, the men who developed ship theory were the same ones who expanded integral and differential calculus and solved the problems of planetary orbits, tides, vibrating strings, and ballistics; ship theory was for them part of the overall study of rational mechanics. Several navies—the French navy in particular—worked closely with their scientific

establishments to encourage such research, which they believed would lead to improvements in the construction and navigation of its ships. That knowledge had to be disseminated to both a Europe-wide scientific audience, as well as to an increasingly literate officers corps, through an evolving web of science journals, academy memoirs, and books. Finally, a new system of professionalization—education, training, and career structure for naval constructors—had to be created almost from scratch, in order that this new knowledge of ship theory could be methodically applied to ship design and construction.

The central thread in this complex fabric is the writing and publication of *Traité du navire* (Treatise of the Ship) in 1746 by Pierre Bouguer, who is also the central figure here. Bouguer and his book are emblematic of the sometimes surprising nature of this story. Bouguer was a French mathematician and astronomer, not a constructor, with no experience in building ships. He wrote *Traité du navire*, the first true synthesis of naval architecture, while on the ten-year Geodesic Mission in the Peruvian Andes to measure the figure of the Earth. The book contained no practical instructions for how to build a ship, but explained for the first time how to predict the characteristics and performance of the ship *before it was built*. It pulled together the previous lines of investigation into a coherent whole, thus becoming the single most important source of fundamental ship theory for over a century. One concept in particular—the metacenter as a measure of ship stability—is used to this day.

Given the complexity of the story of naval architecture, I have structured this work so that the contextual elements are woven into the chapters rather than being set apart. This preface provides a rationale and explanation for the work as a whole. The prologue and epilogue tell the story of Bouguer and the writing of *Traité du navire*, to set the stage for the rest of the work. Chapter 1 serves as an overall introduction, establishing the underlying thesis that naval architecture was developed and implemented in response to a bureaucratic need by naval administrations for greater control over their constructors, rather than as a means of optimizing the engineering of ships. The chapter then describes the changing naval and maritime situation in Europe and explains how it provided the catalyst for the development and acceptance of naval architecture as part of ship design.

The three major elements of ship theory that were formulated during this time occupy the central chapters in this book. In roughly chronological order, they were maneuvering and sail theory (chapter 2, which also describes the dissemination of scientific knowledge); ship resistance and hydrodynamics (chapter 3, also explaining rational mechanics); and stability theory (chapter 4, which also looks at hazards of the sea and the development of tonnage rules). Chapter 5 explores the books that had

the greatest impact on the development of naval architecture during this era. Finally, chapter 6 describes the process of professionalization of naval constructors that was the true legacy of this period. The end of chapter 6 provides the general conclusion to this work, describing the leap of naval architecture from French scientists in the burned-out Scientific Revolution, across the English Channel to the British engineers working at the dawn of the Industrial Age.

This account is told from the points of view of both the constructor and the naval administrator, in order to describe not only the developments of ship theory but also how that theory was perceived and used by ship constructors and, perhaps most important, why naval administrators encouraged and financed its development. It looks at the development not only across 2 centuries but also across the navies and nations of Europe, since the flow of ideas and people across borders was continuous even in times of conflict. Indeed, the separation of ship theory development and construction practices by nation is often artificial, as there were strong and continuous links between scientists and constructors of all nations.⁸

Previous Histories of Naval Architecture

Although I state that this is the first critical synthesis of the history of naval architecture, I do not mean that no such history has ever been written. However, none of them has attempted to cover the entire range of topics, and to place them into social, political, and strategic contexts. Some histories have been spectacularly wrong. An 1860 paper on the state of naval architecture confounded the name of a particularly important individual, the Spanish constructor Jorge Juan y Santacilia, with his naturalist colleague Antonio de Ulloa, to arrive at the very un-Spanish name Juan d'Ulloa, a mistake perpetuated through a number of books that touch on naval architecture history.⁹

Historical accounts of the development of naval architecture began soon after the field was born. Jorge Juan y Santacilia, in the preface to his 1771 work *Examen marítimo* (Maritime Examination), thoughtfully provided a long discourse on its history until that time.¹⁰ In 1791, the German translation of Duhamel du Monceau's *Eléments de l'architecture navale* (Elements of Naval Architecture) included a long bibliography of works on the subject.¹¹ The magisterial *Histoire des mathématiques* (History of Mathematics) by Jean Etienne Montucla, which covered such topics as the development of geometry and the calculus, included a surprisingly large section on the history of maneuvering and construction of ships as part of the range of applied mathematics.¹² All these works were simply summaries of events or publications

which, though immeasurably aiding historical researchers, provided little or no critical analysis.

In 1800, the first book alluding to the history of naval architecture, *A History of Marine Architecture*, was printed in Britain by John Charnock. However, it was primarily a standard naval and maritime history, mostly of Britain. Its use of the term “marine architecture” was limited to the earliest ideas of a ship being simply a work of architecture, so it described many ships and their characteristics but did not mention any developments in ship theory.¹³ A small improvement was made in 1851 by the naval constructor John Fincham in *A History of Naval Architecture*, which though another straight naval history (mostly of Britain), was at least prefaced by a 75-page “Introductory Dissertation on the Application of Mathematical Science to the Art of Naval Construction,” and did in fact give some critical analysis of various works.¹⁴ Finally, the truly magnificent (for a naval architect) four-volume textbook *Architecture navale: Théorie du navire* (Naval Architecture: Ship Theory), written in 1890 by the French naval constructors Jules Pollard and Auguste Dubeout, started with a long bibliography of works on naval architecture going back to the 1600s, with helpful commentaries on each.¹⁵

Most historical works of the early-to-mid-twentieth century in this field were concerned with technology, such as the development of steam propulsion or the introduction of iron, and treated developments in naval architecture only as an aside, with limited and often inaccurate information.¹⁶ This began to change in the middle of the century. In 1958, the British ship surveyor William (“Fred”) Stoot delivered a paper titled “Some Aspects of Naval Architecture in the Eighteenth Century” before a combined session of the British Institution of Naval Architects and its French counterpart, the Association Technique Maritime et Aéronautique (Maritime and Aeronautical Technical Association). Combined with its follow-on paper, “Ideas and Personalities in the Development of Naval Architecture,” Stoot provided some of the first analyses of the history of naval architecture that gave it political and scientific context, and went a long way to dispelling some of the misinformation surrounding it. Stoot’s papers remain an essential source of historical insight into the subject.¹⁷

Interest in the subject has been growing since that time, slowly but steadily. In 1979 the German constructor Gerhard Timmermann published a synthesis of the historical developments in geometrical modeling, stability, resistance, and maneuvering from the 1600s until the twentieth century, *Die Suche nach der günstigsten Schiffsform* (The Search for the Most Favorable Ship Form). A short book (only 176 pages), it is more of a flying survey than a critical analysis, and remains difficult to find outside Germany.¹⁸ In 1980, Alfred Rupert Hall delivered a lecture to the Newcomen Society,

titled “*Architectura Navalis*,” that was perhaps the first critical (albeit very brief) overview of the subject by a noted science historian.¹⁹ Since 1990, studies by individuals such as Horst Nowacki and Julián Símón Calero, extensively referenced in this work, have greatly added to the state of knowledge of the subject.²⁰ In short, the historical interest in the development of naval architecture is starting to grow.

What Is Naval Architecture?

In order to write this history, my first task was to define exactly what is meant by the term “naval architecture.” Quite by coincidence, in 1999 the Royal Institution of Naval Architects (RINA) invited members and nonmembers to suggest suitable definitions of “naval architecture” or “naval architect.” Their responses were published in the pamphlet *RINA Affairs* and excerpts were posted to the RINA Web site.²¹ Many of the responses concentrated on who naval architects *were* (“shipwrights with attitude!” said one), or what naval architecture *consisted of* (“combines imagination, artistic instincts, and proven scientific principles, tempered by basic engineering considerations, in designing the means of ocean transportation”), but few explained exactly what naval architecture *is*.

Standard definitions are unhelpful. For example, the *Random House Dictionary* defines it as “the science of designing ships and other waterborne craft”; *Webster’s Unabridged Dictionary* simply says “the art of building ships.” My French and Spanish dictionaries give similar definitions. For my purposes, these definitions are far too expansive—they would include all aspects of conceptualization, design, and fabrication, and would cover the range from log rafts to ocean liners. So I began reading primary sources in order to trace the evolution of the term.

The first known use and definition of the term “naval architecture” was made around 1610 by the Portuguese mathematician and engineer João Baptista Lavanha in his unpublished treatise “*Livro primeiro de arquitectura naval*” (First Book of Naval Architecture): “Naval Architecture is that which with certain rules teaches the building of ships, in which one can navigate well and conveniently.”²² Lavanha consciously used the well-known architectural text *De architectura libri decem* (Ten Books on Architecture), by the Roman architect Marcus Vitruvius Pollio, to outline his theories, thus placing naval architecture as one of the disciplines of architecture. Since the manuscript was made public only in the twentieth century, it is not clear how widely it was circulated at the time, nor whether Lavanha’s definition was well known. However, the same idea was behind the first published use of the term, in *Architectura Navalis* (Naval Architecture), written in 1629 by the German architect Joseph Furtenbach as

part of a six-volume series on architecture that included military, civilian, and recreational architecture. Furttenbach never defined the term, which may indicate that it was already in some widespread use. His writings show that he saw ship design as simply a subset of the range of architecture types.²³ Thus, the first definitions for “naval architecture” really meant “an architecture of the sea.”

But architecture has always had a mathematical basis, especially in terms of proportions, so it became commonplace to link mathematics to naval architecture. In 1579 the British mathematician Thomas Digges promised to write (but never did) a “brieve Treatise of Architecture Nauticall,” which would contain rules and patterns to follow. In 1646 the British expatriate constructor Robert Dudley, living in Florence, wrote that “Architecture Nautical” was concerned with seven types of geometrical symmetry. And in 1677, *L’Architecture navale* (Naval Architecture), by the French constructor Charles Dassié, argued that mathematics had previously been applied to civil and military architecture, but not to naval architecture. He attempted to do so by defining the proportions (e.g., length to beam) to be given to ships with different numbers of guns.²⁴

The term “naval architecture” came into widespread use in most European languages during the 1700s, by then denoting the application of geometry to ship design; for example, one of the early (1776) French textbooks for students was titled *Essai géométrique et pratique sur l’architecture navale* (Geometrical and Practical Essay on Naval Architecture).²⁵

It was during this time that theories of mechanics (e.g., hydrostatics, fluid dynamics, etc.) were being developed and applied to ships. Ship theory thus became linked to naval architecture, a point made clear in *A History of Naval Architecture* (1851), which spoke of naval architecture as a “science of Ship-building,” including laws of resistance of fluids and motions of ships at sea.²⁶ The 1890 French textbook *Architecture navale: Théorie du navire* (Naval Architecture: Ship Theory) noted that naval architecture included the mechanics of floating bodies, which was developed in “successive steps by Science.”²⁷ So by the turn of the twentieth century, the term “naval architecture” contained the notion of science as an integral part of the definition.

At this point I found it necessary to turn to a related but more complex set of questions: What is science? What is technology? What is engineering? How are they connected? Science is usually associated with experimentation, technology generally involves making and using tools to achieve a purpose, and engineering somehow links the two. Once again, standard definitions are unhelpful—especially the ones stating that technology is “applied science.” Historians of science and technology often expand these definitions to include extensive cultural explorations of the professions,

which are too detailed for my use and don't help me set the boundaries of the subject.²⁸ I note that technology has frequently (perhaps most often) been developed without any recourse to scientific theory—witness, for example, the development of the steam engine by the British inventors Thomas Newcomen and James Watt in the 1700s, well before a useful theory of thermodynamics was published in 1822 by the French engineer Sadi Carnot.

But the application of scientific theory to technology is the critical element in my search for a definition of naval architecture, and is most frequently associated with the definition of engineering. Whether through the use of fundamental mathematical theory (e.g., Carnot's laws) or empirically derived data (e.g., steam tables which give experimental values for heat), engineering is aimed at *prediction*—the ability to determine the characteristics and performance of a system before it is built—and is part of the process of creating a technology. It is through such prediction that a technology can be optimized or improved without a complete reliance on trial and error (construct, test, and change). In other words, engineering is sandwiched within the process of creating a technology, somewhere between formulating the concept and building the thing itself. So for my purposes, a useful set of definitions is the following:

Technology The creation of tools or artifacts to achieve a specific purpose.

Science Theoretical explanation of physical phenomena, through the use of fundamental mathematics or empirically derived data.

Engineering The application of scientific theory to the process of creating technology, with the purpose of predicting the characteristics and performance of a technology before it is built.

This brings me to a final set of personal observations before venturing into a definition of naval architecture. Ship design, like any engineering effort, does not begin with scientific principles, but rather with “rules of thumb.” As a naval architect for the U.S. navy, I would begin my design of, say, a destroyer or frigate, using basic rule-of-thumb proportions for length, displacement, and so on. For example, I would set the hull length-to-depth ratio (L/D) at about 10–15; more than 15 generally produces high stresses and makes the hull too flexible (e.g., for accurate weapons alignment), while under 10 means that the structure is not working efficiently, i.e., the minimum thickness for local loadings governs, so the hull steel is thicker (therefore heavier) than is needed for longitudinal strength. The ideal balance is a hull steel thickness that adequately meets both local loads and hull girder loads. This process was not different from the rules of thumb that ship constructors used in the eighteenth century, before

any notion of ship theory was developed. They all understood, even if they could not articulate it in mathematical terms, that if the L/D ratio was too large—if the ship was too long for its depth—there would be cracking and splitting in the frames and planking. The difference between the constructors of three centuries ago and today is that the constructor today takes the additional step of using ship theory to calculate (in this case) the hull stresses, to determine if the structure is feasible and efficient. In other words, naval architecture allows the constructor to predict a ship's characteristics—in this case providing a rational basis for confirming or modifying the constructor's design decisions. Modern ship design begins by using the kinds of rules of thumb known to the most ancient boatbuilders—but science and engineering “inform” the constructor throughout the design and construction process, allowing him or her to predict the characteristics and performance of the ship before fabrication even begins. This concept places naval architecture as an engineering discipline, sandwiched between concept and fabrication in the process of ship design and construction. Which brings me to my definitions:

Ship design and construction The technology of creating the ship, from conception to fabrication.

Ship theory The science explaining the physical behavior of a ship, through the use of fundamental mathematics or empirically derived data.

Naval architecture The branch of engineering concerned with the application of ship theory within the design and construction process, with the purpose of predicting the characteristics and performance of the ship before it is built.

These definitions broadly correspond to the division of knowledge in two standard reference works published by the U.S. Society of Naval Architects and Marine Engineers: *Ship Design and Construction*, which contains practical information on laying out and building a ship but makes almost no reference to theory, and *Principles of Naval Architecture*, which is completely theoretical.²⁹ I emphasize that these definitions are solely for my purposes in putting some boundaries on this work.

Some Notes on Usage

Royal navies Many navies were royal, not just the British navy, so I refer to them by nation.

Shipyard and dockyard Shipyard is the generic term; it could be as simple as a slipway for construction. I use dockyard to denote the more complex industrial facilities, generally with drydocks for repair.

Constructors I use the word “constructor” to denote the men who designed and built ships, regardless of the era. In each nation, the terms evolved over time and carried different meanings; in English, for example, the term “shipwright” encompassed a wide range of professions—not only hull design and construction but also mastmaking and building oars, blocks, and small boats. In French, the early title *charpentier* meant “carpenter,” the same as furniture maker, but later the terms “constructor” and “engineer” were used. In Danish, the terms *skeppskonstruktør* and *fabrikmester* meant “shipbuilder” and “master fabricator.” The Venetian word *proti* normally meant “shipwright,” but later the term *architetto* (architect) came into use. For my purposes, the single term “constructor” avoids confusion among all these titles and, more important, dispenses with the connotations that each one brings.

Formation I use the term “formation” to describe the combination of education, both elementary and more advanced, and on-the-job training. It is a French word that has no current equivalent in English, but should.

Names and titles As a rule I use the birth names of individuals (e.g., Johann instead of Jean Bernoulli, or Giulio Mazzarini instead of Jules Mazarin), though in some cases I will provide the other name in parentheses, especially if it was more common. Many of the important people in this work were landed gentry, and it was common practice to refer to them by the title of the estate they owned; for example, Jean-Frédéric Philippe Phélypeaux, count of Maurepas, was usually called Maurepas even though his family name was Phélypeaux. I note here that although most Spanish authorities refer to the constructor Jorge Juan y Santacilia as simply Jorge Juan, I use his entire surname to be consistent within this book.

Translations I include the English-language translation of most works at least once per chapter for easier reference; all are translated in the bibliography. I use the English-language names for institutions and places wherever possible.

Ships I refer to warships by the number of guns and not “rates,” as the designation of rates according to firepower (first rate = 100 – 120 guns, etc.) varied between nations. I refer to ships as “it” instead of “she,” conforming to the practice of the influential maritime newspaper *Lloyd’s List* as of 20 March 2002.

Terms, Symbols, Units of Measure, and Money

I generally avoid using archaic technical terms and symbols, although I define them where used, and provide modern symbols from the 1988 edition of *Principles of Naval Architecture*.³⁰ This avoids confusion where one author uses B for center of buoyancy, another uses C, and another uses I. I have also converted most measures of length, weight, and so on into modern SI (metric) values, with the exception of sea distances in nautical miles and speed in knots, which is common maritime practice today. Where I have cited prices or costs, I have given an approximate modern value in U.S. dollars for the year 2002. Below are some specific definitions and conversions that I use throughout this work.

Ship Terms

Length	distance from ship's bow to stern
Beam	width of ship
Depth	height of ship from keel to open deck
Draft	immersion from waterline to bottom of keel
Freeboard	clearance from waterline (e.g., to a deck or a gun port)
Displacement	Weight of ship or, more accurately, weight of displaced water
Admeasurement	measurement of cargo capacity, usually volume (in tuns)

Scientific Terms

Force	a vector quantity that produces acceleration
Pressure	force per unit area
Energy	force times distance

Symbols

A = area

a = acceleration

B = center of buoyancy

g = acceleration due to gravity

G = center of gravity

$\overline{GM}$ = height of metacenter above G

F = force

h = height

I = moment of inertia

M = metacenter

m = mass

P = pressure

R = resistance

S = surface (usually area)

T = period (of time)

V = volume

v = velocity

α or θ = angle (usually of incidence)

Δ = displacement (weight)

ρ = density

Units of Measure

Britain		France	
1 inch	2.54 centimeters	1 <i>pouce</i>	2.67 centimeters
1 foot	30.5 centimeters	1 <i>pied</i>	32.0 centimeters
1 yard	0.91 meter	1 <i>toise</i>	1.95 meters
1 pound	0.435 kilogram	1 <i>livre</i>	0.489 kilogram
1 ton	0.870 tonne	1 <i>tonneau</i>	0.985 tonne

The term “ton” can describe both weight and volume, so to avoid confusion, I will generally use “tun” and “tunnage” for volumetric measures (admeasurement), and “ton” and “tonnage” for weights and displacements.

I provide 2002 U.S. dollar equivalents for most prices cited in the text. Although it is very tricky to convert the money of two and three centuries ago to present values (not only were the commodities different—e.g., horses versus cars—but the proportions of salary spent on, say, housing and food were poles apart), economists have developed estimates of inflation that permit a rough comparison of currencies. The two principal currencies of the period were the French *livre tournois* (literally, the

pound of the city of Tours) and the British pound sterling. Currency conversions vary by year, so to simplify matters I take the midpoints of the two centuries under study (1648 and 1750) as an average value for each century.³¹

Approximate values in U.S. dollars (2002)

1600s	1 pound sterling = \$69.00	1 <i>livre tournois</i> = \$10.00
1700s	1 pound sterling = \$160.00	1 <i>livre tournois</i> = \$6.80

Acknowledgments

First and foremost, to my wife Mirna, who was present at the creation and there throughout.

Although many people assisted me in this work, I list here (alphabetically and by nation) those whose help was absolutely indispensable to its completion.

Australia Stephen Gaukroger, University of Sydney

Belgium Frans Cerulus, Katholieke Universiteit Leuven (Catholic University of Leuven)

Britain Richard Barker, water engineer; David K. Brown, naval constructor and naval historian; Robert Iliffe and Caroline Treacey, Imperial College London; Brian Lavery, National Maritime Museum, Greenwich; Nicholas A. M. Rodger, University of Exeter; James R. Smith, chartered surveyor; William “Fred” Stoot, Lloyd’s Register (retired)

Canada John Harbron, Canadian Institute of Strategic Studies; Roland Lamontagne and Brad Loewen, University of Montreal

Denmark Jakob Seerup and Mogens Anthon, Orlogsmuseet (Naval Museum), Copenhagen

Ecuador Nelson Gómez, Universidad Católica del Ecuador (Catholic University of Ecuador), Quito

France Hubert Berti, ANCRE Publications, Nice; Jean Boudriot, maritime historian; Catherine Bousquet-Bressolier, Université de Paris 1 (University of Paris 1); Geneviève Bresc-Bautier, Louvre Museum, Paris; Jean-Jacques Brioist, Service de la Navigation du Nord-Pas de Calais (Navigation Service of the North-Pas de Calais), Lille; Jean-François Caraës, Archives Départementales de Loire-Atlantique (Departmental Archives of Loire-Atlantique), Nantes; Hugues Chabot, Université Lyon (Lyon University); René and Ghislaine Chesnais, Société des Amis du Croisic (Society of the Friends of Le Croisic); Gérard Delacroix, historian; Jean Dhombres and Hélène Vérin, Centre Nationale de la Recherche Scientifique (National Center for Scientific Research), Centre

Koyré, Paris; Danielle Fauque, Université Paris–Sud 11 (University of Paris–South 11), Orsay; Philippe Henrat, Archives Nationale (National Archives), Paris (retired); Sylviane Llinares, Université de Bretagne Sud (University of Brittany South), Lorient; Gérard Louyot, Conservatoire National des Arts et Métiers (National Conservatory of Arts and Trades), Paris; Eric Rieth, Musée de la Marine (Naval Museum), Paris; Patrick Villiers, Université du Littoral (Littoral University), Dunkirk

Germany Jobst Lessenich, naval architect; Horst Nowacki, Technischen Universität Berlin (Technical University of Berlin)

Italy Cristiano Bettini, Accademia Navale (Naval Academy), Livorno; Gilberto Penzo, historian; Alessandro Ronconi, Museo Storico Navale (Naval Historical Museum), Venice; Guglielmo Zanelli, historian

Netherlands Ab Hoving, Rijksmuseum, Amsterdam; Alan Lemmers, Instituut voor Maritieme Historie (Institute for Maritime History), The Hague

Peru Eliecer Vilchez Ortega, SENATI, Lima

Russia Gleb Mikhailov, Vserossiisky Institut Nauchnoi i Tekhnicheskoi Informatsii (All-Russian Scientific and Technical Information Institute), Moscow

Spain Jorge Juan Guillén Salvetti, Fundación Jorge Juan (Jorge Juan Foundation), Madrid; José Maria de Juan-García Aguado, Universidad da Coruña (University of La Coruña), El Ferrol; Julián Simón Calero, Instituto Nacional de Técnica Aeroespacial (National Institute of Aerospace Technology), Madrid

Sweden Jan Glete, Stockholms Universitet (Stockholm University); Olof Pipping, Vasamuseet (*Vasa* Museum), Stockholm; Thomas Wright, Kungliga Tekniska Högskolan (Royal Technical Higher School), Stockholm

United States of America James Campbell, U.S. navy (retired); Elizabeth Fargo, University of Virginia, Charlottesville; John Hootman and Dana Wegner, Naval Surface Warfare Center, Carderock Division, West Bethesda, MD; David McGee, Dibner Institute, Cambridge, MA; Philip Sims, Naval Sea Systems Command, Washington, DC; Ben Trotter, Ohio State University, Columbus; and various staff members of the Office of Naval Research, Arlington, VA, and London.

Any errors in fact, translation, or analysis are my own.

Ships and Science

Prologue: Down from the Mountain

Naval architecture was born in the mountains of Peru, in the mind of a French astronomer named Pierre Bouguer who never built a ship in his life. Bouguer wrote his monumental work, *Traité du navire, de sa construction et de ses mouvemens* (Treatise of the Ship, Its Construction and Movements), while serving on the ten-year Geodesic Mission in the Peruvian Andes, under the aegis of the French Academy of Sciences, to measure three degrees of latitude that would help define the size and shape of the Earth. Although other theoretical works on ship design had been written before, they were generally focused on a specific subject—maneuvering, for example—and were of little practical use to the shipbuilder. *Traité du navire* was unprecedented, for it was the first work to provide a complete set of principles that governed scientific naval architecture—hydrostatics, hydrodynamics, stability—and it was the first to provide useful mathematical tools for the ship constructor. It was the seminal work in naval architecture, for it laid the groundwork for all future scientific research in that field, and became the bible of ship constructors for almost a century. Before *Traité du navire* there had been no set of laws to guide constructors on the characteristics and behavior of the ships they designed; Bouguer, working alone in the mountains of Peru and far removed from the sight of the ocean, codified those laws and brought them back to France. It was an extraordinary work created under extraordinary circumstances. How *Traité du navire* came to be written is the story of how naval architecture came down from the mountain.

Pierre Bouguer

Pierre Bouguer (figure P.1) was a prolific scientist and mathematician who made highly important contributions to many fields, yet was never considered a luminary in his day and is almost unknown today. He has been rightly called the “father of naval architecture,”¹ especially for his invention of the metacenter, but most naval



Figure P.1

Pierre Bouguer. Pastel by Jean-Baptiste Perroneau (1753), Louvre. Credit: Réunion des Musées Nationaux/Art Resources, New York.

architects—even in his native France—have never heard of him. He was the first scientist to systematically study photometry, the quantitative measurement of light, but his seminal law of atmospheric absorption of light was rediscovered after his death and is known today as the Beer–Lambert law; Bouguer’s name rarely appears in this context.² The great Geodesic Mission to Peru, where he was ultimately responsible for the incredible accuracy of the measurements, was—and today continues to be—credited to his colleague Charles-Marie de La Condamine, with Bouguer and the other members barely receiving a footnote. Bouguer’s name is best known in conjunction with gravity maps that geologists develop to plot gravitational anomalies (differences in the densities of the Earth’s crust), for oil and mineral exploration and for navigation; he discovered these anomalies while on the Geodesic Mission.

Bouguer left little in the way of personal notes or correspondence, and few accounts of him survive. His only published biography, *La Vie et l'oeuvre de Pierre Bouguer* (The Life and Work of Pierre Bouguer), by Roland Lamontagne, though providing a good cross section of his accomplishments, is really a short collection of letters and memoirs by and about him and contains little in the way of personal information.³ Across three centuries, it is difficult to take the measure of the man. He was considered gentle, was well loved by his friends and by many colleagues, and brooded over his mother and brother, his only family. A child prodigy, he brimmed with self-confidence from an early age. Although gifted in higher mathematics, he was eminently practical and almost always expressed his ideas in concrete terms of numbers and dimensions, rather than leaving them in abstract mathematical notation. In adulthood this former prodigy was fiercely vain of his intellect, and did not suffer fools gladly. He could be aloof and condescending, and though he was a good judge of character, he was not politically astute and never fully grasped the intricate social rituals of his day, believing that scientific reasoning should stand on its own merits. This naïve faith in science over politics would plunge him into a dispute that would mark his later career and to a large extent deny him a more prominent place in history.

Pierre Bouguer (pronounced boo-GAYR, in the Breton manner) was the son of Jean Bouguer and Marie Françoise Josseau. Jean Bouguer was born in 1652, and though his initial career is not known, he served 10 years at Brest in the navy, probably as an ordinary seaman. He was a veteran of the aborted 1689 French invasion of Britain, during which he was wounded at Bantry Bay, Ireland, and lost a leg to amputation, forcing his retirement from the navy. In 1691 he moved to Le Croisic, a pleasant coastal town about 60 kilometers from Nantes, near the mouth of the Loire River. He was the first professor at the newly formed School of Hydrography, established by Minister of the Navy Jean-Baptiste Colbert, marquis of Seignelay, to teach navigation and piloting to merchant ship officers. (Le Croisic had a large fishing fleet and a sea salt industry requiring many coastwise cargo vessels for transport). He married Marie Josseau in 1695. Their first son, Louis François, was born in 1696 and lived only nine days. Pierre was born on 10 February 1698, and his younger brother, Jean (sometimes Jan), was born 2 May 1701.⁴

The family presumably lived in the moderately sized house shown in figure P.2, which doubled as the School of Hydrography and was enlarged in 1712 to accommodate the increased number of students wishing to be taught by Jean Bouguer. A large part of his fame came from his 1698 publication of *Traité complet de la navigation* (Complete Treatise of Navigation), one of the first major treatises on the subject, which went through two printings. From an early age Pierre Bouguer was surrounded



Figure P.2

Bouguer's (presumed) family home in Le Croisic.

by students learning mathematics and navigation, and apparently played with astronomical and nautical instruments as toys. His childhood and lifelong friend Paul des Forges Maillard, only a year younger, lived just around the corner. Forges Maillard (to whom Bouguer dedicated a book on astronomy) would grow up to be one of the most famous poets of his age, competing with Voltaire.⁵

Little is known of Pierre Bouguer's childhood. He was apparently educated at the Jesuit school in Vannes, about 100 kilometers from Le Croisic. His eulogy, written by the secretary of the Academy of Sciences, Jean-Paul Grandjean de Fouchy, claimed that Bouguer was so adept at mathematics that he began teaching it at age 11, and at age 13 he won an argument with another mathematics professor, forcing the latter to leave the country in shame. However, as the science historian Danielle Fauque has noted, neither of these accounts is supported by other evidence, and in fact both are cast in doubt, given that the Jesuit curriculum consisted almost entirely of humanities and had almost no mathematics and sciences.⁶

Jean Bouguer undoubtedly taught his son a great deal of mathematics as well as hydrography and astronomy; and Pierre, by now recognized as a child prodigy, would

soon make good use of this knowledge. In May 1714 Jean Bouguer died, leaving his young family without income. The navy needed to fill the professorship immediately, to teach the backlog of pilots-in-training. Pierre, just 16 years old, went to Nantes to apply for his father's now-vacant post, in order to support his brother, mother, and grandmother. Although the navy officials were taken aback by Bouguer's request—he was, after all, very young, and in any event they had another candidate in mind—they agreed (after a flurry of correspondence with the Ministry of the Navy) to examine him for the position. He passed the exam, and in June 1714 was given the position of professor of hydrography at Le Croisic, where he would teach students twice his age the fundamentals of navigation and piloting.⁷

Bouguer's life seemed set in Le Croisic, where he remained almost 20 years. Once again, little is known about this period of his life. In addition to teaching 600–700 pilots,⁸ he undoubtedly taught his younger brother, Jean, who would eventually take his place as professor. He managed to support his family, though the position of hydrography professor did not pay well—around 1,000 *livres tournois* (\$10,000) per year in 1691. Bouguer, in his later letters to the minister of the navy, would continually ask for money, and in 1749 his brother, Jean, who had by then taken over as hydrography professor, got into trouble with the tax officials for nonpayment of taxes.⁹ I speculate that for Pierre Bouguer, teaching quickly became mundane and he sought more challenging pursuits, ones that would stretch his intellect. The course of his life would change after he met the retired mathematics professor Charles René Reyneau on a trip to either Angers or Paris, apparently in an effort to obtain guidance on the newly developed calculus. Reyneau's 1708 *Analyse démontrée* (Analysis Demonstrated) was one of the first textbooks on the Continent to explain the calculus, and Bouguer would naturally have sought him for an explanation of its finer points, although Bouguer probably taught himself much of it. Reyneau, impressed by Bouguer, provided him an introduction to Jean-Paul Bignon, president of the French Academy of Sciences, the center of political power in the sciences. Bignon, in turn, recommended Bouguer to Jean-Jacques d'Ortous de Mairan when the navy called upon the Academy in 1722 to assist in a study of admeasurement of ships.¹⁰

Bouguer's careful evaluation of two competing methods for measuring the cargo capacity of ships, by testing them on two little harbor vessels, proved invaluable to Mairan, who became his strong supporter. Even though Bouguer was just 23, his foot was already in the door of the Academy. When two years later, in 1724, he sent the Academy a treatise on the masting of ships, Mairan ensured that it would be the subject of a prestigious prize that Bouguer won in 1727 with his memoir “De la Mâture des vaisseaux” (On the Masting of Vessels), a veritable minitreatise on the field of naval

architecture. He cemented his reputation at the Academy in 1729 with another prize for the best way of observing the altitudes of stars at sea, followed by one on the gradation of light. The two prizes also gave him a nice sum of money, 2,000 *livres tournois* each (a total of \$27,000 today).

The Academy of Sciences had traditionally strong ties with the French navy, and this was especially true under Minister of the Navy Jean-Frédéric Philippe Phélypeaux, count of Maurepas, who was honorary vice president of the Academy and cousin to Jean-Paul Bignon, president of the Academy. Bignon had evidently ensured that Maurepas took note of Bouguer's work on admeasurement, and suggested that the minister support Bouguer in his further work on improving navigation and naval architecture. Maurepas quickly became Bouguer's strongest supporter in both naval and Academy matters, and by 1726 a close working relation had developed between them as Maurepas continued to assure his advancement.¹¹ Bouguer's treatise on masting had touched on several important areas of naval architecture, including resistance and stability, but it became evident to him after submitting his prize entry that the existing theory in those areas was deficient. Most treatises at the time were concerned with describing in detail how to design and build ships, providing methods and specific proportions or hull lines to follow, but almost none provided any clear rationale or theory for the choice of those proportions and lines.

Sometime in 1730, Bouguer met with Maurepas in Paris, where the minister of the navy gave him orders to continue working on masting and to carry out some experiments. However, in October of that year, Bouguer expanded those ideas, proposing to Maurepas further investigation not just of masting, but also of "the laws of fluids," by theory and experiment. (He also asked for more money).¹² Maurepas by this time considered Bouguer one of his most important scientists, and took steps to ensure he would remain close to hand. In December 1730, Bouguer asked for, and was quickly granted, the vacant post of hydrography professor at Le Havre (Havre-de-Grace), the most important hydrography school in France at the time and much closer to Paris. He took the post in June 1731, and his younger brother, Jean, assumed Pierre's position in Le Croisic. On 5 September 1731, when he was just 33, Bouguer was given the title of associate mathematician ("geometrician") by the Academy on the strength of his memoirs and two Academy prizes.¹³

Little is known about Bouguer's tenure at Le Havre, not even where he lived. In the event, his stay would last only from June 1731 to May 1735. Although he had teaching duties, Bouguer spent an increasing amount of time engaged in research on astronomy and ship theory, submitting ten memoirs to the Academy of Sciences and receiving his third prize. This meant numerous trips to Paris, for which the

government paid him a supplement; while he was away, Bouguer assigned “master experts” to take over his classes.¹⁴ Bouguer’s most important work in ship theory was carried out in Le Havre. In addition to numerous experiments and calculations on the laws of fluids (including the bow of least resistance), he was also investigating the strength of ropes and wood.¹⁵ Most significantly, Bouguer apparently began formulating his theory of the metacenter and ship stability while he was at Le Havre, for, as described in chapter 4, he tested it using the little 18-gun frigate *Gazelle*, laid down in the Le Havre dockyard in May 1732.¹⁶ The metacenter would become the most important development of early naval architecture, and in fact is the only theory surviving to the present day.

Gazelle was finished in January 1734. In that month, Bouguer wrote a pivotal letter to Maurepas, describing his work on ship theory thus far:

[The honor of your protection] is for me a powerful motive to sustain me in the most dismal undertakings . . . [as well as] to overcome the different problems I have encountered in the Work with which I am occupied, and which I will, with your permission, MONSEIGNEUR, have the honor to describe to you. . . . I am convinced that one can make a considerable [advance] by making more clear the practices of the Constructors; and instead of insisting on the manner of tracing curved lines, one insists on the manner of choosing between these lines, and to discover, without always being forced to rely to experience, the properties that they [the ship’s lines] have with regard to the construction.¹⁶

Bouguer went on to argue that one could build excellent ships without knowing precisely why they were so, or why one method was preferred over another.

It is this incertitude that I am trying to dissipate in the Treatise on which I am working: I have in view, as I have already had the honor to explain to YOUR GREATNESS, not so much to trace the plans of vessels as to show how to choose between the methods of tracing plans, and to reduce to a simple and easy calculation the advantage and disadvantage of each shape. Once a plan is proposed, I endeavor to discover just how far the ship to be constructed will be immersed in water, to see if the battery is high enough; to determine how fast with relation to the wind the ship will go; to determine if it will carry sail well; and finally to discover if it will obey the helm quickly enough. All these things depend on the shape and weight of the vessel, and are by consequence the result of geometry and mechanics; and I believe I can put them to a simple and easy test so they may be within reach of those with even the simplest grasp of mathematics. . . . So here, MONSEIGNEUR, is the plan of the Work to which I am devoting all my time.¹⁷

Thus did Bouguer so clearly outline what would become his *Traité du navire*, which allows us to fix an approximate date of 1733/1734 for the start of its composition. He clearly stated the case for exploring not another set of lines and proportions to follow in building a ship, but a method for analyzing them *before the ship was built*. In particular, he provided Maurepas with a tantalizing glimpse of his work on the

metacenter by relating the whole performance of the ship to its shape and weight. He was becoming engaged in a line of research aimed at developing a complete theory of the ship. Yet this line of inquiry suddenly stopped almost as soon as it was begun. He did not continue his research into the metacenter on the now completed *Gazelle*, and there was no further correspondence on the subject. Bouguer's attention, like that of the rest of the Academy, had turned to the question of the Earth's shape, and he would not return to naval architecture until he was high in the mountains of Peru.

The Geodesic Mission to Peru

The Debate over the Earth's Shape

By early 1734, the French Academy of Sciences was in the midst of a debate on the shape of the Earth, which had in fact begun a century earlier. The French philosopher René Descartes had developed, in 1644, a vortex theory of motions that relied on a swirling ether to carry planets and create gravity. By contrast, the British mathematician Isaac Newton, in his 1687 *Philosophiae Naturalis Principia Mathematica* (Mathematical Principles of Natural Philosophy), provided a completely different set of theories that showed gravity to be a mysterious attractive force that acted at a distance, with no physical mechanism for transmission. The French Academy of Sciences saw the support of Descartes's theories as a matter of national pride, even in the face of mounting experimental evidence that Newton had it right. This resulted in a stream of Academy memoirs and prizes that attempted to merge Newtonian mechanics with Cartesian vortices. One of the outcomes of Descartes's theory was that, due to the vortices, the Earth was a prolate spheroid (i.e., lengthened at the poles). The director of the Paris observatory, Giovanni Domenico Cassini (succeeded by his son Jacques) had carried out geodesic surveys in France from 1683 to 1718 that supported this view, showing (erroneously, as it happened) a noticeable enlarging of a degree of arc from north to south. Newton, however, argued that due to centrifugal forces, the Earth was oblate (i.e., bulged at the equator and flattened at the poles). (See figure P.3).¹⁸

So the debate between Descartes and Newton really came down to a question of Earth's shape, and that represented more than just a polite academic squabble. Knowledge of the the exact size and shape of the Earth was essential for accurate navigation on the oceans. This was a time when navigational science was heavily supported by most European nations; the famous prize under the 1714 Longitude Act in Britain, which offered £20,000 (about \$1.4 million today) for accurate determination of longitude, was still up for grabs. Therefore, the question of prolate versus oblate spheroid had immediate interest for Maurepas, not only as vice president of the Academy but

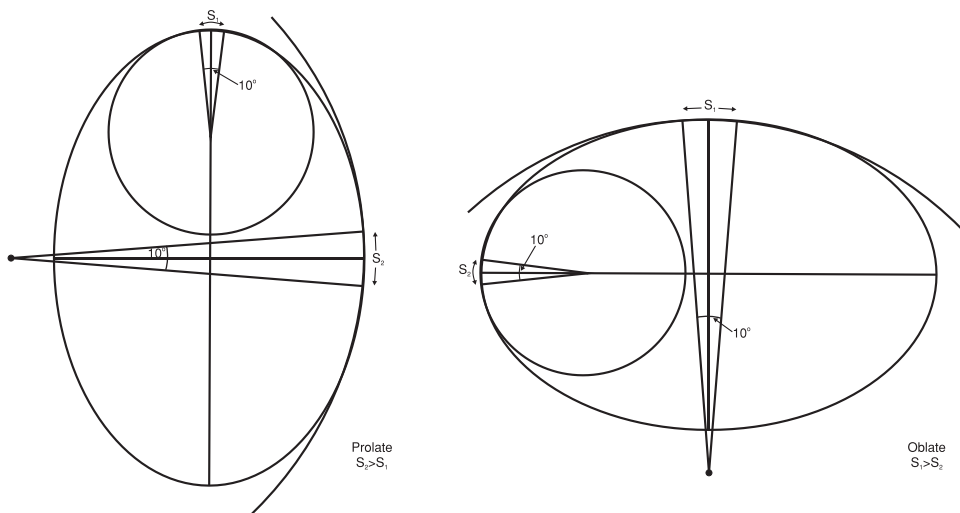


Figure P.3

The prolate spheroid of Descartes and the oblate spheroid of Newton.

also as minister of the navy, which included responsibility for the colonies and merchant trade.

It had long been recognized that the best way to determine the shape of the Earth was to make separate observations as close to the equator and the poles as possible, in order to compare the length of an arc of latitude at each location. As shown in figure P.3, an oblate spheroid would show a shorter arc of latitude at the equator than nearer the poles. Since Cassini had already determined the length of the arc in France, an expedition to the equator or near the pole would provide another measurement for comparison. In June 1733, three members of the Academy (the mathematician Pierre Louis Moreau de Maupertuis, the astronomer Louis Godin, and the explorer and chemist Charles-Marie de La Condamine), who had been working on the question of the Earth's shape separately, presented memoirs arguing for such an expedition. Such an undertaking required far more resources than the Academy alone could provide; it would need the full backing of the royal treasury, which Maurepas was prepared to support.¹⁹

In fact, it required more than just money. From the start, the Academy and Maurepas had settled on an expedition to the equator, and it was obvious that it would have to be somewhere in South America, since Africa was still largely unexplored and the islands of Southeast Asia were too distant. They believed from the few maps they

possessed that the double chain of mountains in the Spanish viceroyalty of Peru (in present-day Ecuador), known as the Cordillera de los Andes, would provide excellent observation points for a geodesic survey. From the comfort of an armchair in the Louvre in Paris, this appeared to be impeccable logic.

Maurepas quickly made overtures to the Spanish court, which since the end of the War of the Spanish Succession in 1714 had been in the Bourbon family alliance with France. The first letters went out in February 1734, and by May the Spanish secretary of state, José Patiño Rosales, gave his conditional approval. Maurepas soon took charge of the entire planning, obtaining passports and letters of credit for use in Peru, ships for passage, instruments, and provisions. The Mission was initially to be led by two of the proposers, Godin and La Condamine, as well as the astronomer Jean-Paul Grandjean de Fouchy, all men in their thirties. Over the course of 1734 the list of members changed several times, as men bowed out when faced with the reality of the voyage. In particular, Grandjean de Fouchy claimed to have been “attacked with a long and dangerous malady,”²⁰ and someone had to take his place.

In March 1734, three months after Bouguer had described to Maurepas his plans for *Traité du navire*, he read before the Academy the results of his new research on geodesy that had so suddenly diverted his attention from naval architecture. This paper, modeling the shape of the Earth as a rotating mass of fluid, pointed out flaws in Newton’s original arguments on the equilibrium of rotating spheres.²¹ It caught Maurepas’s attention and marked Bouguer as a potential candidate for the mission. Although Maurepas began tasking Bouguer with astronomical research, Bouguer was apparently unaware of his intentions, being surprised to learn that Maurepas had requested a quadrant (a geodesic device) be sent to him.²²

On 18 December 1734, Jean-Paul Bignon wrote to Bouguer, stating that Maurepas had asked him for advice on who should replace Grandjean de Fouchy, and that he had suggested Bouguer; Bignon reminded him of the importance of the mission and assured him that all expenses would be paid. Meanwhile, Maurepas made certain that Bouguer would accept by ensuring that he received a promotion to “pensioner astronomer,” filling a vacancy Bouguer had been competing for (against two more experienced astronomers) since May. Bouguer quickly accepted, and on 28 December he met with Bignon in Paris, affirming his decision and preparing for the voyage.²³

The Geodesic Mission Takes Form

Preparations were now in full swing, but from the start it was evident there would be problems. Louis Godin was not the oldest or most experienced of the group, but as

he had been in the Academy the longest and held the highest position there, was assumed to be the nominal leader. However, none of the instructions from Maurepas specifically charged him with overall command, which would lead to later difficulties. Bouguer was assumed to be second in command. La Condamine, who now held Bouguer's former position of associate mathematician, was not skilled in astronomy or mathematics. He appears to have been chosen more for his military background (he had been a soldier and had seen action in the Mediterranean expeditions of the corsair René Duguay-Trouin) as well as his political connections (he was a close friend of François Marie Arouet, known as Voltaire, whom he made rich in a lottery scheme). Several assistants would help with the measurements: Jean-Joseph Verguin, a civil engineer and draftsman from the Toulon dockyard; Jean-Louis de Morainville, an illustrator and draftsman; Théodore Hugo (sometimes spelled "Hugot"), a clockmaker, to repair instruments; Jean Godin des Odonais, a young cousin of Louis Godin, acting as a "chain-bearer"; and another chain-bearer, Joseph Couplet de Viguier, nephew of the Academy treasurer Nicolas Couplet de Tartreux, himself a veteran of a South American expedition.

Since this would be the first extended European look at the Spanish colony of Peru, Maurepas ensured that the Mission would include the botanist Joseph de Jussieu, whose brothers were famous naturalists at the Academy, to record the flora and fauna; and Jean Seniergues, the company surgeon, who would assist Jussieu. In the meantime, Prime Minister Patiño of Spain had decided that a group of French scientists should not go into his viceroyalty without proper supervision, and requested that two naval cadets from the Academy of Navy Guards be appointed to assist the group and keep an eye on them. Jorge Juan y Santacilia (then only 22 years old but recognized as a mathematical genius) and Antonio de Ulloa y de la Torre-Guiral, 19 years old and gifted in the natural sciences, were appointed, vaulting four grades to lieutenant.

Back in Rochefort, the 44-gun *Portefaix* was armed *en flûte* (i.e., lower gun decks cleared of cannon to take cargo), carrying provisions, books, and instruments for the voyage, including firearms, swords, and gunpowder.²⁴ While the French members of the expedition waited, the first indications of trouble surfaced. In April 1735, Bouguer complained to Maurepas of the condescending treatment he was receiving from Godin, and expressed doubts (prescient, as it would happen) that Godin would participate equally in the scientific work. *Portefaix* finally set sail from Rochefort for Petit-Goâve in the French colony of Saint-Domingue (present-day Haiti) on 11 May 1735, and in Cadiz, Spain, the 70-gun *Conquistador* (with Juan y Santacilia) and the 58-gun *Incendio* (with Ulloa) left on 23 May, bound for Cartagena de Indias (in

modern-day Colombia). The facts that the expedition set sail on warships, and that the members were heavily armed, were thought of as prudence, but in reality were harbingers of things to come.

After a stopover in Martinique, *Portefaix* arrived in Petit-Goâve in July 1735, and the expedition members stayed until October. It was at this point that the fundamental flaw in the expedition became apparent, one that would cause the premature deaths of several members and nearly result in its complete failure. Godin, as nominal leader, took sole charge of the finances without any controls or oversight. He had left behind a wife and two children in France. However, he began an affair with a woman whose taste ran to the extravagant and, determined to keep her in fine style, had spent much of the expedition's money by the time they left Petit-Goâve.

The French members finally met Juan y Santacilia and Ulloa in November in Cartagena de Indias. After sailing to Porto Bello in Panama and an overland crossing of the isthmus (during which time they began learning Spanish), they sailed down the Pacific coast. Bouguer petitioned Godin to abandon the idea of ascending to the Cordillera almost 2 kilometers up, and instead make the measurements along the coastline, in much easier conditions. Godin was already feeling his authority, always precarious since Maurepas had never officially named him leader, slip even further, perhaps to counter this perception, he stubbornly refused to abandon his preconceived plans. By now animosity between Godin and Bouguer was running very high. The group split up and took separate paths to the provincial capital, Quito, arriving in June 1736, almost a year after they had started.

Back in France, interest in the Peru expedition was already waning. In part to keep the expedition in the public eye, Voltaire composed and staged a rather run-of-the-mill tragedy, *Alzire ou les américains* (*Alzire, or the Americans*), set in Lima and portraying the noble natives oppressed by evil colonial rulers.²⁵ Maupertuis, having been left out of the Peru expedition, proposed a second expedition to Lapland (modern Finland) to obtain complementary measurements closer to the North Pole, which was approved by Maurepas and promised to give results in much less time. Accompanied by scientists such as Alexis Clairaut, Pierre-Charles Le Monnier, and Charles Étienne Louis Camus, the expedition was supported by the Swedish Academy of Sciences, whose staff included Anders Celsius. The group left France in May 1736 and went north to the top of the Gulf of Bothnia, near the town of Torneå. Their observations would be much less extensive and far less accurate than what would ultimately be produced in Peru, but they returned to France in August 1737, after being away just over a year.²⁶

By contrast, the men who set out for Peru in 1735 had thought they would be gone at most three years: six months out, two years of observations, and six months back. Instead, they arrived in Quito already behind schedule, and suffered further delays as their funds ran out. La Condamine had to make an eight-month trek to Lima, the capital of the viceroyalty, to negotiate for more money to keep the expedition going. Seniergues found that his skills as a surgeon could bring him a very good income. Hugo and Morainville took occasional jobs in Quito to replace the funds Godin had depleted.²⁷

Triangulation

The task that the Geodesic Mission had set out to accomplish was to measure three degrees of latitude along a single north-south meridian stretching from Quito to a point 350 kilometers south (about the distance from New York to Washington, D.C.) to compare with the measurements taken in France. The technique, known as triangulation, had been perfected in the 1600s and was used by the Cassinis during their survey of France. A straight baseline several kilometers long was established and measured on flat, open ground. The surveyors then used accurate quadrants to measure the angles from each end of the baseline to the apex of the first triangle, a visible marker such as a pile of stones. They continued creating a chain of triangles (figure P.4), measuring the angles to each apex. After series of long, iterative trigonometric calculations to obtain the distance between the extreme north and south ends of the chain, the arc length (the difference in latitudes) would be determined by star sightings. Dividing the arc length by the total distance gave the length of 1 degree of latitude.²⁸

By September 1736 the expedition members were ready to begin the survey. While reconnoitering a flat plain at Cayambe, northeast of Quito, Couplet fell violently ill with malaria, and three days later he died, on 19 September. He was the first of the expedition to die, and the youngest. After his burial in the church at Cayambe, the expedition returned to their survey and found, probably with some relief, that it was not suitable for the baseline. They turned their attention to a plain about 35 kilometers east of Quito, called Yaruquí.

Today Yaruquí is covered with greenhouses in which magnificent roses are grown for export. They are shipped by truck to Quito airport in about an hour, and within forty-eight hours they can be at almost any florist in the world.²⁹ In 1736 it was two days' hard journey from Quito, over hills and across steep gorges to get to the large farms that dotted this spit of land. The expedition found this reasonably flat terrain

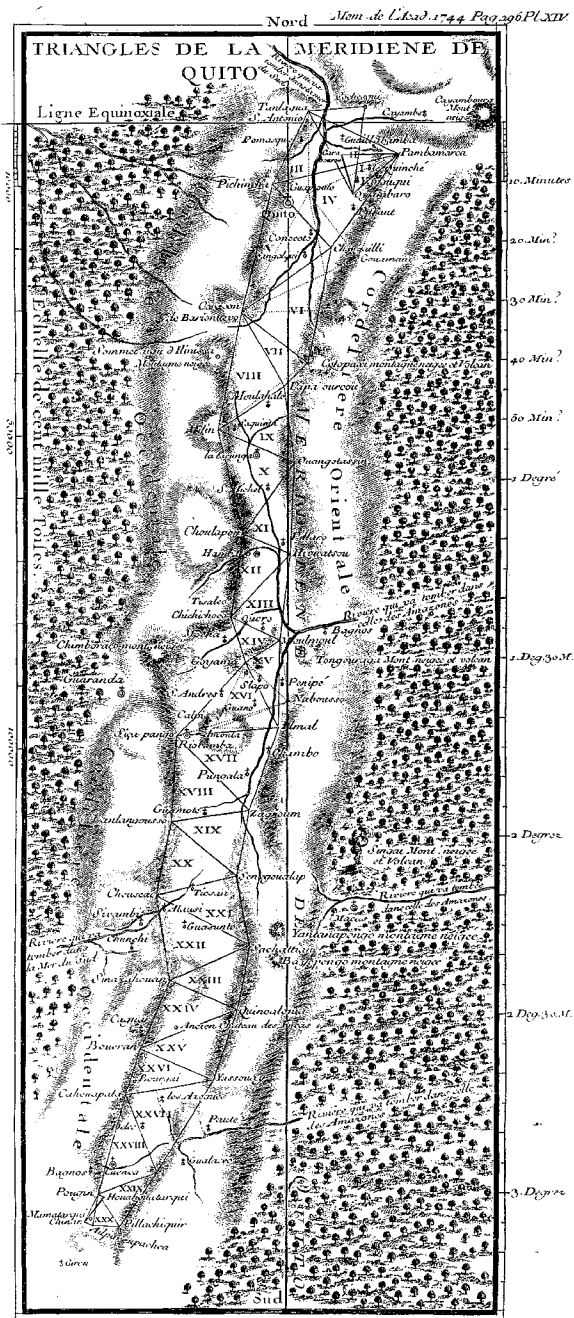


Figure P.4

The Geodesic Mission's survey triangles along the Cordillera. (Bouguer, "Relation abrégée du voyage fait au Pérou" [1744], p. 296). Credit: Archives de l'Académie des Sciences, Paris.

to be adequate for their purposes, and with the aid of La Condamine's friend, a local official named Pedro Vicente Maldonado, found local laborers to help carry the supplies from Quito. But "flat" was a relative term when trying to lay out a level baseline between two points that were 6,200 *toises* (about 12 kilometers) apart. Today, within the first 100 meters from the southern end of the baseline the land suddenly drops 1 meter, then there is a 2-meter vertical drop, and just beyond is a thicket of heavy shrubbery. The landscape in 1736 was probably not much different, and every change in elevation had to be carefully accounted for and every obstacle overcome. To create the baseline, an absolutely straight path half a meter wide and 12 kilometers long had to be dug into and ripped up and scraped out of the landscape. It was two months of backbreaking work for these normally sedentary men: uprooting shrubs, cutting down trees, breaking through stone walls, blowing up rocks, fording ravines, stopping for breath every ten minutes in the rarefied air, traversing the entire distance on hands and knees for the painstaking measurements which were carefully compared with a standard *toise* that they had brought from France. From this point on, the expedition would live in tents and huts for almost all of the next three years.³⁰

The next step was to begin surveying the long chain of triangles down the Cordillera. As it consisted of a double series of peaks with a wide valley between (see figure P.4), there was, in theory, a clear view between the summits for locating the apexes of the triangles. At this point the comfortable decisions taken back in the Louvre must have appeared ludicrous. These mountains soared 2,000 meters over the plains and were separated by 30 or more kilometers; getting from one apex to another could take several days. The frequent clouds made visibility almost nil for long stretches. Still, the members were committed to the task. The expedition split into two teams, in order to have two independent sets of results; Bouguer, La Condamine, and Ulloa were in the first team, and Godin and Juan y Santacilia in the second. In June 1737 the teams began surveying the chain of triangles.

The various accounts by the members of the expedition tell the same story. It was not the heat, but the cold, which affected them most. At an altitude of 4 kilometers, the nights were bitter in their little tents and huts, and they were often assailed by hailstorms and blizzards whose violence had no equal in Europe. They became mountain climbers, scaling the lofty peaks to make the necessary measurements, creating rude encampments where they could, and waiting for the weather to break in order to sight their marker signals on the next peak. Bouguer once was lost for two nights in a cold, damp fog, and almost at the end of his strength when he was finally located. They ate little—some boiled chicken and rice, and melted ice to drink. Their signals,

made of wood and stone, were often carried away by the local Indians, so they took to using their tents and huts as markers. Days passed into weeks, and weeks into months as slowly, inexorably, the 32 triangles were laid out, until in July 1739 they at last arrived in Cuenca, where they set up and measured a second baseline at nearby Tarqui to confirm the results.

Revenge and War

The expedition's second death was, in retrospect, all too foreseeable. While the astronomers were making their triangles, the two doctors, Joseph de Jussieu and Jean Seniergues, were making botanical observations as well as treating the sick. Jussieu was beginning to make inquiries and experiments regarding smallpox inoculations, seeing how mildly infected people developed a resistance to later, more virulent infections. Seniergues, on the other hand, though no longer forced to practice medicine for money, found the income too agreeable to give up. This alone would have been enough to turn the population against him, but he was indiscreet in his affairs with women, in what was still a very conservative culture with a highly refined code of honor. He had begun courting a 20-year-old named Manuela Quesada on his first visit to Cuenca in 1737, and immediately had run into trouble, as she was the fiancée of a prominent townsman, Diego de León. Seniergues had been forced to leave Cuenca, but now that the entire expedition was there to mark the end of the survey, he courted Manuela again.

León was itching for a fight, and given the general sentiment of the population against the French (in part, they believed the French were looking for gold and other riches), he knew he had the townspeople with him. On 29 August 1739, Seniergues was at a bullfight with Manuela Quesada and her family; Bouguer, La Condamine, and other members of the expedition also were in attendance, on the other side of the ring. In the middle of the bullfight, an argument broke out between Seniergues and some of León's friends, and quickly escalated into a mob assault against Seniergues. The other members of the expedition saw what was happening, but were too far away to do anything; Seniergues collapsed with several stab wounds. Bouguer and La Condamine drew their swords and attempted to cover their escape; Bouguer was slashed across his back as he retreated into a nearby house. Seniergues died three days later despite Jussieu's ministrations. Bouguer recovered well enough to start his astronomical observations. In July 1740 he went to Guayaquil to ascertain the height of the Quito plateau; along the way he had to live on fruit and fish because "half [his] supplies were carried off by tigers."³¹

By early 1741 it became apparent to Bouguer that the astronomical observations he and La Condamine had carried out over the previous year did not agree, and so had to be redone. (Godin was no longer a factor.) La Condamine, tired and homesick, suggested that they simply split the difference. Bouguer, although just as anxious to return, was horrified at the idea of inexactness. Thus began Bouguer's battle with La Condamine, which would last the rest of his life.

But measuring the figure of the Earth was getting far more complicated than a simple fight between two men; a war was breaking out. In October 1739, Britain and Spain began what would become known as the War of Jenkins's Ear, a prelude to the War of the Austrian Succession. Spanish Peru began preparing its coastal defenses against a British assault, and as Jorge Juan y Santacilia and Antonio de Ulloa were Spanish officers first and foremost, regardless of their duty to aid the French, the viceroy of Peru called them to Lima to help repair the ports of Callao and Guayaquil. No attack came, but the two officers were sporadically absent from 1740 until 1743, including a year at sea vainly searching for George Anson's fleet, which would eventually circumnavigate the globe in search of Spanish warships.

The Last Days of the Geodesic Mission

Louis Godin had by now completely stopped work, and did not communicate the results he did obtain. In June 1742, Bouguer and La Condamine set out for Quito to prepare their final set of astronomical observations to establish the arc of the meridian. On the way, they toured the volcanoes of the Cordillera, including Chimborazo, a dormant volcano that was widely believed to be the highest mountain in the world. Bouguer had previously visited the mountain in 1738, to perform an experiment to determine the variations in gravity caused by the mass of the mountain (they would later come to be called Bouguer gravitational anomalies). The two men also climbed to the summit of Pichincha, an active volcano, to look into its crater.

La Condamine next went south to Cuenca while Bouguer stayed in Quito. Between December 1742 and January 1743 they each observed the star Epsilon Orion. Runners delivered the figures to each party; the calculations were made; the arc had finally been measured. Eight years of effort reduced to one simple number, the length of a degree of latitude at the equator: 56,750 *toises* (110,610 meters).³² But Bouguer's letter to La Condamine contained other news: he was leaving Peru immediately. He had finished his business there, and he saw no reason to wait for the other members of the expedition. As the expedition's funds were now exhausted, he asked Jussieu for a share of Seniergues's estate. Bouguer left Quito on 20 February 1743 in the company of

Miguel de Santisteban, a local official, and went overland to Cartagena de las Indias to await a ship home.

Writing *Traité du navire*

Bouguer had taken only a temporary hiatus in 1734 when he stopped work on his treatise of naval architecture in favor of geodesy. When he was called to join the Geodesic Mission, it was natural, if not somewhat bizarre, that he would continue this work while in the Andes, during what he knew would be a prolonged absence. Tucked in between the astronomical instruments and provisions loaded aboard *Portefaix* were books and papers pertaining to ship theory, which were laboriously carried up to Quito and all along the Cordillera. In his dedication of *Traité du navire* to Maurepas, Bouguer recalled that Maurepas had appointed him to the task of helping advance the progress of naval science, and that, while in Peru,

neglecting nothing to carry out your orders, I took every moment I could allow myself to work on the composition of this Treatise . . . the desire I had to offer this to you sustained me against extreme difficulties, which came not only due to the nature of the subject, very complicated in itself, but also of the situation in which I found myself.³³

Bouguer himself admitted that this task was rather anomalous. In a letter to the French scientist René Antoine Ferchault de Réaumur, dated 12 April 1738 (during a brief respite in Quito), Bouguer quipped:

You will no doubt have trouble guessing with what I am now occupying myself on our snow-capped mountains, where one must wait entire months for the clouds to permit seeing the countryside and not cover the sky. There is absolutely no observation to be done and it is necessary that the Astronomer occupy himself with something else. I am passing my time meditating on the construction of vessels and writing a Treatise. I am trying to finish it here, in order to then weigh up the rules at leisure, for as far as it will be possible, on the voyage that we will make to return to France.³⁴

In the preface of *Traité du navire*, Bouguer echoed this observation:

working on this Book, in the highest mountains of the world, where I tried to not waste the weeks and months it took sometimes to get a single instant of good weather, so as to be able to attend to the actual operations of the measure of the Earth.³⁵

In fact, the records of the expedition show that Bouguer and his colleagues would frequently spend anywhere from a week to a month at each mountain survey station, before obtaining a clear day to make a sighting. For example, in the spring of 1738 they spent two weeks on the volcano Cotopaxi (shown on the cover) without a single clear day, and returned later that summer to finally make their observations.

Bouguer apparently completed his manuscript in 1740 or 1741.³⁶ As noted earlier, Bouguer outlined the idea of the treatise to Maurepas in early 1734, after which he became involved in the study of geodesy, so it is likely that he made little progress while in France during 1734–1735. He probably wrote part of *Traité du navire* during the voyage to Peru (1735–1736), and at least some of it in the relative comfort of his observatory in Quito (1736–1737, 1740–1741), where he could make liberal use of the references he must have brought with him. But a good portion of *Traité du navire*, must have been written in the field (1737–1739), in the face of personal disputes, sword fights, and death; and, by Bouguer's own accounts, often while high in the mountains. The difficult conditions under which it was written make it even more amazing as a seminal work of eighteenth-century science. We can imagine Bouguer in his tent at night, perched on a narrow Peruvian mountaintop, the wind howling outside and sheets of freezing rain beating a staccato on the drenched fabric, warmed by a small coal fire. He writes by flickering candlelight in his clear, proud hand; page after page of calculations pour out onto sheets of foolscap, followed by lines of text in his manuscript; a few books there, perhaps, but mostly his intellect and his mathematics to determine the laws that govern the characteristics and behavior of ships.

As will be noted later, Jorge Juan y Santacilia would go on to become Spain's chief naval constructor, and would later write one of the most important works of theoretical naval architecture, *Examen marítimo, teórico práctico* (Maritime Examination, Theoretical and Practical).³⁷ Did he collaborate with Bouguer on writing *Traité du navire* during the Geodesic Mission? Undoubtedly no. Although brilliant, Santacilia was a 23-year-old novice when the expedition arrived in Peru, while Bouguer was 38 and had been a professor since Juan y Santacilia was a year old, so there was little the Spanish lieutenant could offer him. His own *Examen marítimo* would not appear until 25 years later, so he probably had not even considered those kinds of problems until much later in life. Juan y Santacilia spent most of his time with Godin and not with Bouguer (in fact, he often acted as a go-between for the two), so it is unlikely that the two were even friendly. I suspect that, despite the apparent coolness of their relationship, Juan y Santacilia held Bouguer in awe; Bouguer may even have told him of his ideas on the metacenter and fluid resistance before they were published, though there is no evidence or correspondence to prove or disprove this. I speculate that, both through the influence of Bouguer and the circumstances of his career, Juan y Santacilia found himself attracted to the same subject later in his life.

Bouguer stated that he had written his book in Peru, in order that on his return voyage he could “recognize if there were something to be changed”—which, as will be seen, he did. He stated that on the eve of his departure from Quito, he left a second

copy “in the hands of a reputable person” to serve as duplicate, presumably in case something happened to him during his return. No trace of this duplicate manuscript has yet been found.³⁸

The Impossible Return

The funds provided by Maurepas had run out, and no more were forthcoming. The French members of the Geodesic Mission were forced to find their own means back to France (or not), and the human toll of this oversight was terrible. The minor members suffered most. Hugo and Morainville remained in Peru, later collaborating on a silver mine; Hugo married and lived out his days in Quito, while Morainville, who apparently left a wife in France, died from a fall of scaffolding in the church of Sicalpa, sometime between 1757 and 1760. Jean-Joseph Verguin finally scraped together enough money to leave in June 1745, returning to Toulon to find that his wife was dead and his two children were in the care of their grandmother; he resumed his career as a civil engineer for the navy at Toulon, where he died in 1777.³⁹ Joseph de Jussieu traveled the Andes for several years, collecting botanical specimens never before examined by Europeans (all of which were eventually lost), and spent five years as a doctor in the silver mines of Potosí, the principal source of Peru’s wealth and a living hell for the workers. Jussieu eventually borrowed enough money to return to France in 1771, but by then he was apparently in the grip of mercury poisoning from the silver mines, losing his speech and mental capacities, and dying in 1779.⁴⁰

Being Spanish naval officers not dependent on the French Academy for funds, Jorge Juan y Santacilia and Antonio de Ulloa took separate French warships back to Spain. Juan y Santacilia eventually arrived without complications, but Ulloa’s ship was captured by a British warship and brought to London. After a short time he was released and, unexpectedly, made a Fellow of the Royal Society for his work in Peru. Together they wrote two separate accounts of their expedition. One was for public consumption, revealing to Europe the almost unknown world of Spanish Peru. The other was a dark, scathing description of the corruption and harshness of the vicerealty, intended only for government ministers.⁴¹ Ulloa would go on to a career as a naturalist and statesman, returning to Peru as a provincial governor and later governing all of Spanish Louisiana. Juan y Santacilia would play a central role in the development of naval architecture, as will be seen throughout this work (figure P.5).

Louis Godin took a position as astronomer at the University of San Marcos in Lima, having lost all credibility with the French Academy of Sciences. Perhaps in a small way he achieved some redemption, for when Lima was devastated by an earthquake



Figure P.5

Jorge Juan y Santacilia. Oil by Rafael Tejeo (1828). Credit: Museo Naval, Madrid.

in October 1746, Godin was placed in charge of reconstruction, a post in which he designed what would become one of the most beautiful cities in South America; his work is visible even today in Lima's older sections. He returned to France for a few months in late 1751, though as he no longer had a position at the Academy of Sciences, he went on to Spain, where, at the intervention of Ulloa, he was named the head of the Academy of Navy Guards and first director of the observatory of Cadiz. Godin died there in 1760.⁴² La Condamine, accompanied by Pedro Vicente Maldonado, took a spectacular voyage down the Amazon, becoming the first European to extensively document the river and its environs.⁴³ La Condamine would go on to have a distinguished career in France, but Maldonado would die in London in 1748, possibly from measles (to which he had no resistance), after being feted by the French

Academy of Sciences and the British Royal Society. Inspired by La Condamine's good fortune, Jean Godin des Odonais would later descend the Amazon without his Peruvian wife, Isabel, and would wait 18 years in Cayenne for her to make the trip. Of the ten people she finally left with, only she emerged from the jungle, barely alive; she and her husband finally returned to France in 1773, the last members of the Geodesic Mission, 38 years after it had begun.⁴⁴ The works of La Condamine, Juan y Santacilia, and Ulloa, the accounts of Isabel Godin's adventure, and the introduction to Europe of quinine, cinnamon, and (most important) rubber by the returning members of the expedition, would motivate a new generation of naturalists and explorers to go to South America, most notably Alexander von Humboldt. In turn, the extensive contacts the members of the Geodesic Mission made throughout South America would inspire a revival in the sciences by later individuals such as the Colombian naturalist and astronomer Francisco José de Caldas. When Ecuador became independent in 1830, the notoriety of the Geodesic Mission gave the new nation its name.⁴⁵

Pierre Bouguer arrived in Cartagena de Indias in September 1743 after eight months of trekking, and found a ship to take him to Léogane in the French colony of Saint-Domingue. The colony had many sugarcane plantations that provided France with its sugar, so it was only a matter of time before a ship would sail for France. Bouguer stayed in the colony, rewriting his notes; while waiting, he ran out of money, so he borrowed from the colony's intendant. In November, the 150-ton slave ship *Triton* from Nantes (one of the largest European slave-trade ports) arrived with 406 Africans to work the plantations. It would not depart for France for several months, and Bouguer received authorization to depart on this ship in January 1744. *Triton* finally left in March 1744, loaded with barrels of raw sugar and carrying seven passengers, including one weary astronomer. The fact that it was a slave ship did not bother Bouguer; like other members of the expedition, he had bought a slave in 1735 during his initial stay in Saint-Domingue. He had assisted during part of the initial geodesic surveys in Peru before he was murdered.

Compared with the first two legs of *Triton's* triangle-trade journey from Nantes to Africa to Saint-Dominigue, on which 11 sailors and 34 slaves died of disease or drowned, the return voyage was relatively uneventful; only two sailors died. Bouguer trained the first officer, Pierre Fouré du Pellerin, in the art and science of navigation. He also took the opportunity to make several observations on the rolling of the ship, perhaps revising some of his original ideas that he had written while in Peru, and which he would later record in his final version of *Traité du navire*. On 28 May 1744 the little ship sailed into Nantes harbor.⁴⁶ Pierre Bouguer had returned, and was ready to bring the laws of naval architecture down from the mountain.

1 “Mere Carpenters”

Toward the end of the last century, Europe had not any theoretical work on navigation, except for pilotage. The Construction of Vessels was abandoned to mere Carpenters; and it was not considered that NAVAL ARCHITECTURE was based on a constant application of Mechanics and Geometry, which are the most difficult branches of Mathematics.

—Pierre Lévêque, *Examen maritime*, translation of Juan y Santacilia: *Examen marítimo*, (1783), p. ix

This narrow and disparaging view of early ship constructors as “mere carpenters” was originally expressed by the Spanish constructor Jorge Juan y Santacilia in his work of theoretical naval architecture *Examen marítimo* (Maritime Examination).¹ The French professor of hydrography Pierre Lévêque, in his fairly loose translation quoted above, added the notion that constructors were incapable of applying theory to design.² Lévêque’s words were picked up by the British constructor John Fincham in his 1851 book *A History of Naval Architecture*, and quoted extensively by historians afterward.³ Many contemporary observers of the field also held the opinion that constructors who built ships without having a theoretical basis for their designs were somehow inferior to other naval professionals. In 1755, the Dutch vice admiral Cornelis Schrijver, in a well-publicized attack on Dutch constructors, claimed that they were “nothing more than carpenters” because they had no command of naval architecture on geometrical grounds.⁴ British naval officers were particularly scathing in their opinions of constructors, an especially surprising viewpoint given that their navy’s continued control of the sea was due in large part to their quite effective ships. Officers regarded surveyors, who were in charge of design and construction, as “jumped-up carpenters” with no more social status than warrant officers, lamenting that “the man who first thought of appointing carpenters to direct the construction of the navy has a grievous sin to answer for.”⁵

Nothing could be further from the truth. In the 1600s and 1700s, the period in which this work is centered, ship constructors were highly trained professionals who knew the practical uses of arithmetic and geometry for their craft, but often had little

formal education—many could neither read nor write—because it was unnecessary to their occupation. Much of their working lives was spent in the shipyards learning and applying the craft of ship construction, not in schools and academies trying to learn mathematics and mechanics that would serve no useful purpose for them. They often worked under considerable stress as they tried to build and repair ships for navies that were frequently engaged in one war or another. They knew their business and built good ships, not blindly to old ideas but based on sound practice that they themselves improved through experience.

Sailing warships were the most complex engineering structures of their day. They combined the heavy wooden construction of the hull and masts with a dizzying array of standing rigging to support the masts, hundreds of lines and blocks to control the yardarms and sails, capstans for hauling up the anchors, tillers and wheels to turn the rudder, bilge pumps, and such, for which the constructors had overall responsibility to integrate into the ship.

As the French constructor Pierre Forfait noted in 1788:

A vessel is an extremely composite machine, or rather it is a combination of most known machines. To understand the effects of that combination, it is not enough to determine separately what each part is capable of, but moreover to have regard for the diverse relationships that the particular results have with the assembly.⁶

Constructors built these “composite machines” to withstand extraordinary environments of wind and wave, house hundreds of men for months or years at a stretch, fight pitched battles, and last from 20 to 30 years, all within a structure smaller than a typical church. To underline the technological sophistication of ship constructors in creating such compact military machines, it is useful to compare gun-carrying warships with an equivalent gun force for a terrestrial army. As noted by the military historian John Keegan, Napoleon’s army at Waterloo in 1815 included an artillery corps of 366 cannon, requiring 5,000 horses and 9,000 men to deploy it, and it could move only about 20 miles a day before stopping to bivouac. By contrast, Nelson’s fleet at Trafalgar in 1805 consisted of 27 ships carrying 2,200 naval cannon and 14,000 men; the fleet could travel, day and night, over 100 miles a day—and without the enormous quantities of horse fodder that the land army required. In short, the fleet carried six times as many guns as the army, at five times the speed and with one-fifth the logistics cost.⁷ When considering that the same artillery corps might conceivably occupy over 50 hectares of land, while the fleet carried six times the firepower on less than 3 hectares of open deck, the technological achievement of the naval constructor in creating such an efficient fighting platform, without recourse to ship theory or engineering calculations, was impressive indeed.

Given the difficulties of simply keeping pace with these demands, it is surprising that constructors would ever have seen fit to learn and carry out the intricate calculations that theoretical naval architecture required. Ship theory had no obvious advantages for constructors in that era; even Jorge Juan y Santacilia, one of the most important figures in the development of theoretical naval architecture, warned his colleague José Romero Fernández de Landa against relying too heavily on it:

... theory has cost me an infinite amount of labor, and will do the same to you if you try to understand it; it seems to me that it would be better for now to stick to learning practical matters and to see the differences that various constructors use. I won't go into this more because it would take months and years; one day perhaps we'll speak about it, if God grants me enough life to complete my work.⁸

So if ship theory was so problematic and not particularly useful, why was it developed in the first place? What was the role of naval architecture (again, defined as the application of ship theory within the design process), and why and how did it come to be accepted and used by constructors? It was not developed in response to perceived problems with ship design (e.g., poor stability), which were generally solved by practical means; certainly there was no concerted effort to develop ship theory in the way that navigational science was developed in response to the hazards of being lost at sea (notably, inquiries launched by the 1714 Longitude Act in Britain). The time and expense of performing the calculations—and the formation required to be able to do them—were not justifiable in terms of profitability, for either merchant or naval fleets, given that the resulting ships were not markedly faster, more maneuverable, or more stable, as will be seen.

The thesis of this work is that naval architecture was developed and used by various navies, starting in the late 1600s, in response to a bureaucratic need by naval administrations for greater control over their constructors and for standardization of the ship design process.⁹ The systematic use of ship theory made sense only within the bureaucratic organization established for naval construction, which came to include a strong central control of design and a system of professional formation that enabled constructors to carry out the calculations. The demands by naval administrators for theoretical calculations in ship design can be seen as the next logical step from their growing insistence on scale models and ships' plans, as will be discussed shortly.

Ship theory was quickly incorporated in navies where there was already a strong institutional development of scientific naval architecture, notably in France, Spain, Denmark, and Sweden. In those navies, the development of ship theory coincided with—and was integrated into—the standardization and centralization of the design process during the 1700s. This was not the case for the other navies, notably those of

Britain, the Netherlands, and Venice, which had provided little direct support for scientists working on ship theory. The British navy in particular had already refined its bureaucracy and standardization of rates before 1720, well before ship theory had become fully developed; it also relied heavily on commercial shipyards, where eyes were on the bottom line and not on theoretical advances. Nevertheless, continuing pressure by administrators in those navies would eventually lead to the professionalization of their constructors and the eventual adoption of ship theory as part of naval ship design, around the turn of the nineteenth century. By that time, however, the leading edge of development in naval architecture was shifting from government bureaucracies that were part of the burned-out Scientific Revolution to independent engineers attempting to solve practical problems in shipbuilding as the Industrial Age gathered steam.

Overview of the Naval and Maritime Situation in Europe, 1600–1800

If war is policy carried out by other means, as the Prussian strategist Karl von Clausewitz said in several ways in his book *Vom Krieg* (On War), then warship design and construction is also a continuation of a nation's policies. To understand the role that ship design and construction would have occupied in the minds of naval administrators, it is vital to view the world through their eyes by considering the rapidly changing naval and maritime situation during the two centuries that this book covers. In each nation, these administrators were almost continuously preparing their navies for war or actually dispatching instructions for the fight. The logistical effort of sending fleets halfway around the world was enormous. An almost continuous stream of correspondence directed activities on construction, repair, victualing, and crewing; on strategy and tactics to be carried out; on work to be done on port and harbor infrastructure; and much more, often carried out with only a few clerks and officers. The fact that any of them were able to think about developments in naval architecture, much less to provide almost continual encouragement and support for it, is rather astonishing, given this context.

European Navies

Naval conflict between France and Britain was the dominant theme in this period, though the situation was hardly that simple; France was principally a land power, Britain a sea power, and the terms of conflict varied considerably as to the involvement of other nations. Alliances and enemies were fluid, and two nations that had been at war in one year might team up against a third the next. This was nowhere

more evident than the classic British balance of power strategy: to keep any single nation from uniting the rest of Europe against it, Britain would generally back the weaker power against the stronger in a conflict. When Spain was the principal enemy in the late 1500s, Britain backed its rivals. The shifting of power between the Netherlands and France in the 1600s caused Britain to side first with one and then with the other.¹⁰ In the 1700s, the Bourbon family alliance of France and Spain was developed as an effective counterweight to Britain.

Britain was the dominant maritime power for much of this period, for the well-known reason that the nation could be invaded only by sea. Its national policy was to strongly support its navy, which spent more of the national budget than any other government department. Other nations—France in particular—had to defend their land borders and quite logically devoted far more of their budgets to armies. In the 1730s and 1740s, for example, the British naval budget was between two and four times that of France. The level of resources naturally determined the size and deployment of each navy. In the 1700s, Britain was capable of organizing and deploying permanent squadrons across the Atlantic, which was by far the most important operating area for European navies, and would keep them on station in the ocean for long periods of time—what later naval historians would term sea control, although in practice it meant controlling only certain key shipping lanes and vital areas such as entrances to ports. The French navy would only deploy a squadron annually, and Spain kept only a small permanent squadron in the Caribbean, so these two Bourbon nations relied on fortified colonial ports (e.g., the French port of Louisbourg in Canada and the Spanish port of Havana in Cuba) to maintain their overseas presence. With smaller fleets than the British, they tended to avoid major engagements and adopted more "hit-and-run" tactics.¹¹

Table 1.1 gives an overview of the size of the seven navies under study, using the most basic statistic, the number of large sailing warships during representative decades. Galleys and other oared ships are not included. This information, as well as much of this section, is principally derived from *Navies and Nations*, a remarkable comparative study of European navies by the naval historian Jan Glete.¹² In fact, a number of other nations also had significant navies during this period, such as Portugal, Turkey, and Russia, as did city-states such as Naples and Genoa; but I have not yet been able to look into their contributions to the development of naval architecture, so they are not included in this survey nor in this general body of work.

France During the 1500s, a series of civil wars had led to the practical disappearance of the navy, by 1600 leaving only a small galley fleet and no sailing warships. When

Table 1.1

Number of major sailing warships, 1600–1800

	France	Spain	Denmark	Sweden	Britain	Netherlands	Venice
1600	—	?	16	56	34	?	—
1620	3	?	24	34	29	?	—
1640	53	?	43	42	43	97	—
1660	26	?	16	33	131	97	—
1680	135	?	53	28	115	93	7
1700	146	?	42	49	177	113	29
1720	33	29	40	33	155	74	27
1740	59	59	33	33	154	59	9
1760	95	89	42	40	301	57	15
1780	162	125	56	35	286	66	14
1800	110	113	37	24	328	22	—

Source: Glete, *Navies and Nations* (1993), pp. 522–704.

Cardinal Armand Jean du Plessis, duke of Richelieu, became Louis XIII's prime minister in 1624, he took charge of naval and maritime affairs to gain control over the coasts and to protect merchant ships. He instituted a rapid building program and also bought ships, arms, provisions—and naval constructors—from other nations. War with Spain from 1635 to 1659, as well as its own internal revolution (the Fronde) left the navy with only 26 ships when Jean-Baptiste Colbert began his rise to power in 1661. By 1669 he was minister of the navy and building a fleet that would surpass Britain's, with France briefly becoming the dominant maritime power in Europe. To sustain the buildup, Colbert created new Atlantic naval dockyards at Brest and Rochefort while ordering ships from the Netherlands and Denmark; he also backed Renau's work on ship theory, both as a "force multiplier" and as a way to achieve efficiency and standardization. France allied with Britain against the Netherlands from 1672 to 1674, but by 1689 was back at war with Britain, now allied with Spain and the Netherlands. When the British fleet crushed a French invasion force in 1692, the French navy began a long, steady decline, with doctrine shifting from *guerre d'escadre* (line-of-battle warfare) with heavy, expensive ships of the line, to *guerre de course* (commerce raiding), to lighter, faster cruisers, even during the War of the Spanish Succession (1701–1714).

Over the next two decades the French navy was rebuilt under Minister of the Navy Jean-Frédéric Philippe Phélypeaux, count of Maurepas, who, like Colbert, saw naval science (including ship theory) as a strategic asset for his fleet, and strongly supported

Bouguer, Duhamel du Monceau, and others in their research, including financing the Geodesic Mission to Peru (1735–1744). The wars of Jenkins's Ear and of the Austrian Succession pitted France and Spain against Britain and the Netherlands from 1739 to 1748, punctuated by a brief period of furious shipbuilding before the Seven Years War broke out (1756–1763). Another wave of shipbuilding followed, under the reforms of Minister of War and of the Navy Étienne-François, duke of Choiseul, whose 1765 ordinance insisted for the first time on the use of ship theory as part of the design and created the Corps of Engineer-Constructors of the navy. This first corps of constructors went on to design the ships that served in the War of American Independence against Britain from 1778 to 1783. A short rapprochement with Britain ensued until the French Revolution (1789) launched the Revolutionary and Napoleonic wars, resulting in the 1805 defeat of the combined French and Spanish navies at Trafalgar.

Spain Little reliable information is available on the numbers of ships in the Spanish navy before 1715. The failure of the Spanish Armada during the attempted invasion of England in 1588 set the nation on a slow decline marked by occasional spurts of rebuilding. From 1621 to 1648 the navy was engaged in sea battles and blockades during the war of independence in the Spanish Netherlands, then continued fighting France until 1659. In 1688 Spain allied with its former enemies Britain and the Netherlands to fight France again. In 1714, after the War of the Spanish Succession, Spain began to build up its navy and seek the assistance of France, now allied to it as part of the Bourbon empire. At first it had ships built abroad, but from 1720 to 1750, under ministers José Patiño Rosales and Zenón de Somodevilla y Bengoechea, marquis of Ensenada, new dockyards were constructed in El Ferrol, Cartagena, and Guarnizo (at Santander). This first phase of reconstruction was dominated by ships designed under Antonio de Gaztañeta e Iturribalzaga. The War of Jenkins's Ear with Britain (1739–1742), which interrupted Juan y Santacilia and Ulloa during the Geodesic Mission, eventually erupted into the War of the Austrian Succession that lasted until 1748. From 1752 until 1765, Juan y Santacilia created a new fleet of ships using expatriate British constructors he had lured to Spain. The Havana dockyard in Cuba was refurbished after the British left in 1762, and eventually built more ships for the Spanish navy than any other dockyard, including the giant 130-gun *Santísima Trinidad*, flagship of the Spanish fleet at Trafalgar. In 1765 the French constructor Jean-François Gautier was brought into the Spanish navy to help consolidate the two Bourbon fleets. Although a true consolidation of the Spanish and French navies was never achieved, the Spanish fleet continued to grow, joining the French fleet in the War of American Independence in 1779. The apogee of Spanish naval construction

was reached under José Romero Fernández de Landa and Julián Martín de Retamosa. The Spanish fleet, at first allied with Britain and the Netherlands against the French Revolutionary forces, changed sides in 1796, leading to the engagement and defeat at Trafalgar in 1805.

Denmark This navy was more properly known as the Danish-Norwegian navy; Norway had been a Danish province since 1536. The Danish navy had to negotiate the shallow Drogden Strait between Denmark and Sweden, only 7 meters deep at some points, so it could not build the largest ships of the line found in other European navies, and focused its operations in the Baltic. Its principal enemy in the 1600s was Sweden; these were short conflicts in 1611–1613 and 1643–1645, during the Thirty Years War. A war with Sweden from 1657 to 1660, and a forced peace settlement in 1678, led to a strengthening of the navy, and by 1690 a policy of nationalization of shipbuilding was begun under Admiral Henrik Span, resulting in the expansion of the Holmen naval base at Copenhagen. Within a few years, the Great Scandinavian War with Sweden (1709–1720) eroded the fleet, leading to a long period of relative if uneasy peace that allowed naval cadets to follow up their rigorous training in shipbuilding with extensive visits to many foreign shipyards. The highly trained officer-constructors of the Danish navy, notably Henrik Gerner, developed quite innovative designs during the slow reconstruction of the fleet, with warships performing such duties as convoy escort. This peace would last until 1801, when the Napoleonic Wars reached the Baltic, eventually leading to the loss of Norway to Sweden in 1814.

Sweden As mentioned above, Sweden was in intermittent conflict with Denmark during the 1600s (as well as with Russia, Britain, and the Netherlands), resulting in several fleet buildups that included the construction and capsizing of the 64-gun *Vasa* in 1628. From 1700 to 1720 Sweden was almost continuously engaged in small-ship battles with Russia and Denmark. This led to the creation of a galley Inshore Fleet to protect the Finnish coast against Russia. The navy attempted to standardize its designs from 1760 to 1780, eventually appointing Fredrik Henrik af Chapman as chief constructor who oversaw a brief period of rapid reconstruction. An inconclusive war with Russia from 1788 to 1790 and the 1792 assassination of Chapman's supporter, King Gustavus III, led to the rapid demise of the navy.

Britain This section represents England before the 1707 Act of Union with Scotland created the nation of Great Britain. The defeat of the Spanish Armada in 1588 had increased the standing of Britain in Europe. Its alliance with the Spanish Netherlands

in the 1620s showed that strengthening the navy with commercially hired ships was a poor practice, and after the Civil War (1642–1648) a fleet buildup began, in which constructors such as Peter Pett and Anthony Deane achieved notoriety. Wars with the Netherlands from 1652 to 1674, and then with France from 1689 to 1692, were grueling, but Britain eventually emerged as the supreme naval power in Europe after the War of the Spanish Succession, and remained so until 1740. During this period, the British navy adopted its Establishments that successfully standardized the shipbuilding process. The War of the Austrian Succession and the Seven Years War led to a major fleet buildup, facilitated by the extensive contracting of warship construction to commercial shipyards, an option not available to (or not used by) Spain and France, which did not have anything like Britain's commercial financial markets. Although Britain lost several key battles to French and Dutch forces during the War of American Independence, its sheer size and the quality and training of its officers and crews allowed Britain to dominate the oceans during the French Revolution and Napoleonic Wars that lasted until 1815.

Netherlands Although ostensibly a republic in 1609, the Netherlands did not achieve full independence from Spain until 1648, after which reliable ship lists appear. Its fleet was reduced as an economic measure, but during the three Anglo-Dutch wars (1652–1674) it rapidly built up its fleet, until by 1670 it was the leading sea power in Europe. Within a decade, however, it dropped behind Britain and France. From 1690 onward, it was allied with Britain against France, a situation that allowed Dutch ships to be integrated with British squadrons, and for the Admiralty to hire British constructors for its Amsterdam dockyard; on the whole this situation permitted the Netherlands to concentrate on building a fleet of smaller ships to protect trade and colonies. Its involvement against Britain in the War of American Independence in 1780, combined with other interests, led the Dutch to rebuild their battle fleet. In 1795, the newly formed Batavian Republic allied with the French Revolutionary government against Britain, but in spite of a massive building program the British fleet destroyed major elements of the Dutch navy in 1797 and prevented others from deploying. Dutch warships served as part of the French fleet until the Kingdom of the Netherlands was formed in 1815, after Napoleon's fall.

Venice This is the only city-state considered in this general work. The Venetian navy was the dominant maritime power in the Mediterranean during the 1500s, principally through its galley fleet, for which its famous dockyard, the Arsenal, was purpose-built for assembly-line construction. Venice fought against Turkey from 1645 to 1669 with

galleys and armed merchant ships. The first sailing warships of this era were built in 1667, requiring a considerable change in construction methods; instead of quickly building lightly framed oared ships in large series production, the constructors were now designing and building heavily framed 60- and 70-gun sailing ships in much smaller numbers. They learned quickly, for those ships soon fought, largely successfully, against the Turkish fleet from 1683 to 1689 and again from 1715 to 1718. During the long period of relative peace that followed, a considerable number of hulls were left on their building ways in the dockyard. In the 1760s the Republic of Venice began a renovation of the fleet that eventually included a new school of naval architecture under the architect Gianmaria Maffioletti. This was short-lived, for in 1797 the city fell to Napoleon's invading armies and was turned over to Austria. France took it back in 1806, and the dockyard was placed under French authority until 1814.

Merchant Fleets

Although the French minister Jean-Baptiste Colbert is most often associated with mercantilism, almost every nation in Europe practiced it in one form or another. From the 1200s to the 1500s a complex network of small, independent shipowners and shipbuilders had developed all around Europe, but by the 1600s a group of powerful state-supported companies came to dominate oceangoing trade. The first joint-stock trading companies, beginning with the English Muscovy Company in 1555, were established in part to provide raw material for the burgeoning state industries, as well as for the navies and armies. The British East India Company, chartered in 1600, and the Dutch Verenigde Oostindische Compagnie (United East Indies Company, or VOC), established in 1602, quickly became the principal rivals for maritime trade. The Dansk Ostindien (Danish East India Company) was established in 1616, and went through two more incarnations in 1670 and 1732. Several German overseas trading companies were formed in Brandenburg between 1632 and 1721. The French government entered the race quite late with the Compagnie des Indes Orientales (East Indies Company) in 1669, formed after Colbert had grown increasingly angry as he watched French colonial production end up in Dutch warehouses. In Trieste, the Compagnia Orientale (Oriental Company) was set up in 1719, one of the last of the great trading companies to be formed.¹³

These companies were what would be termed today "vertically integrated," often combining overseas goods production (frequently in the form of slave plantations for cotton and sugar), ships and shipbuilding, docks, warehouses, and domestic manufacture and marketing. The merchant fleets sometimes resembled state navies, and in

many cases the distinction between a commercial company and a public authority was lost.¹⁴ These merchant fleets could negotiate on behalf of the national governments, and even wage war—which they frequently did with rival companies. Although state navies would often provide warships for convoy escort, many cargo ships were themselves heavily armed for self-protection, carrying as many guns as a frigate. In some cases, these “merchant navies” outnumbered the state navies; for example, in the 1660s the Dutch VOC had 40 warships and 150 merchant ships, compared with 100 warships in the Dutch navy.¹⁵ The economics of these companies were also interwoven with national politics, as demonstrated by the fact that the three Anglo-Dutch wars (1652–1674) were fought (in part) over the possession of trade routes, as well as the rights of the Dutch VOC and the British East India Company to do business in one another’s harbors.

State and merchant navies would not only swap officers, but also would share construction facilities and even constructors. In the Netherlands, for example, Pieter Pauluszoon van Zwijndregt and Willem Udemans Junior were constructors at VOC dockyards before moving to Admiralty dockyards in the 1760s.¹⁶ The British navy would take East Indiamen under contract as warships, for they were built as stoutly as frigates; in fact, the same dockyards built both East Indiamen and naval warships, sometimes under the supervision of the same surveyor.¹⁷ In France, the Lorient dockyard in Brittany, originally created in 1666 for the East Indies Company, was home to the navy for many years before the company took it back in 1719. Like other companies in Europe, the French East Indies Company frequently exchanged constructors with the navy (e.g., Pierre Coulomb and Antoine Groignard). Unlike other companies, it also invested in the development of ship theory, although on a much smaller scale than the navy. For example, it evidently instigated a 1765 French Academy of Sciences prize on ballasting and lading (see chapter 4), and supported the extensive ship resistance experiments in 1768–1769 of Antoine-Jean Marie, count of Thévenard (described in chapter 3), whose results it might have used had it not gone bankrupt in 1770.

Doctrine, Technology, and Ship Theory

The naval and maritime situation from 1600 to 1800 was as convoluted as at any period in history, an almost continuous series of wars on both the state and the mercantile fronts, combined with a complicated interplay of alliances and partnerships between naval and merchant fleets. In order to understand how and why ship theory came to play an increasingly important role in this constantly changing environment,

it is necessary to analyze how science, technology, and design influenced, and were influenced by, the changes in operational doctrine that resulted from the shifting political and military situations.

In current U.S. military parlance, “doctrine” defines the fundamental principles that guide forces in support of objectives, encompassing the ideas of “strategy” (developing and employing forces to achieve objectives) and “tactics” (the arrangement and maneuver of these forces).¹⁸ Although it is a military term, “doctrine” can also apply to commercial activities, especially concerning the merchant fleets in that era. Of course, the term “doctrine” did not exist as such in the maritime parlance of the day, but its impact on the use and handling of ships was well understood, if not explicitly expressed. It created the requirements for infrastructure such as dockyards and overseas ports, determined the fleet order of battle, and dictated the deployment of squadrons. Therefore, doctrine was the lens through which technical and scientific innovations were examined; if they were seen to improve the design or operations within that framework—or if they significantly changed that framework to the navy’s advantage—they became accepted.¹⁹ The following paragraphs list several examples of evolution to naval and maritime doctrine that were catalysts for changes in science, technology, and ship theory.

Naval Combat Using Heavy Cannon

Small guns had been used at sea since before 1400, but generally as infantry weapons during the common tactics of ramming and/or closing with the enemy ship to board it with infantry troops. Heavy cannon appear to have come into use beginning around 1450, but at first they were deck-mounted and did little to change the ram-and-board doctrines. All this meant that, in practice, there was little to distinguish sailing warships from sailing merchant ships (rowed vessels such as galleys and galleasses were another matter). In the early 1500s, the concept of cutting gun ports into the sides of sailing ships allowed at one stroke a massive increase in firepower, as (eventually) several tiers of cannon could be mounted in the hull; naval doctrine evolved to favor longer-range, gun-to-gun battles, though this was still often a prelude to boarding. However, constructors had to build heavier framing to support the guns and protect against shot, while providing deeper hulls to ensure that the lower gun tiers (“batteries”) remained clear of the water.

The construction of gun-carrying sailing warships became more specialized during the 1600s, and the investment required to build, operate, and maintain these specialized ships led nations to develop permanent, state-owned navies as opposed to hiring privately owned ships or fitting out merchant ships for war.²⁰ As part of this

specialization, naval constructors began developing methods for calculating the displacement of ships to ensure that their lower batteries had sufficient freeboard to operate.

Line of Battle and Standardization

The incorporation of heavy cannon into sailing warships quickly led to a new type of warfare, the line of battle. By the mid-1600s, doctrine had shifted from emphasizing individual ship engagements to maneuvering a fleet of ships as a single unit.²¹ As this doctrine evolved, the need for some form of standardization of ships within a line of battle became clear. If one ship was lost to battle damage, adverse winds, or other factors, the fleet commander would need to replace it quickly with another ship of similar capabilities, such as radius of action (dictated by victualing capacity), maneuvering, and artillery configurations. Tactical planning was also far easier when the fleet commander could make general assumptions for his entire battle line, rather than accounting for individual differences in ship performance.²²

Standardization had an additional benefit that any modern manager faced with budget constraints would appreciate. By standardizing the numbers and types of equipment in a fleet, administrators could significantly reduce the costs and logistics of building and maintaining new kit and spare parts, in particular, the myriad types of masts, spars, lines, pulleys, and yards in the sailing rig.²³ It should be noted, however, that the concept of standardization in the era of craft-built wooden ships did not extend to the modern idea of series production and learning curves. Even so, the advantage of reducing outfitting costs was not lost on merchant navies; in the 1740s, the Dutch VOC settled on three basic designs for its vast fleet, and by the 1760s the French East Indies Company had achieved some standardization of the sailing rig.²⁴

Even with such benefits, standardization was slow in coming to large sailing warships, as it necessarily evolved with the move of technical authority away from dockyards to a central technical authority. French Minister of the Navy Colbert was one of the first to attempt standardization in 1670, when he divided ships into five rates based on the number of guns (first rate = 70–100 guns, second rate = 56–70 guns, etc). Even after several subsequent regulations (as they were called), the French system was often honored more in the breach than in the observance. From 1765 to the 1780s, a series of reforms led to the standard designs developed by the constructors Jean-Charles de Borda and Jacques-Noël Sané for 74-, 80-, and 118-gun ships that served as the backbone of the French navy until the 1830s.²⁵ In Britain, such rules were called "Establishments," and were successfully implemented more quickly than in France;

the ones of 1719, 1733, and 1745 effectively created a series of common designs for all dockyards. In Spain, several attempts to standardize designs were made, notably under Gautier's efforts to consolidate with the French fleet.

The arguments against such standardization often focused on the notion that it stifled the creativity of individual constructors to explore better designs, and thus inhibited the evolution of naval architecture. While this was perhaps true in principle, in practice it meant little that any individual ship was better if the entire fighting fleet could not benefit; one constructor was not generally inclined to adopt the practices of a competing constructor, even if both worked for the same navy. It was only through a centralized system that any improvements by individual constructors could be disseminated across the entire fleet in a uniform manner.

Extended Operations at Sea

An example of how differences in doctrine led to divergent scientific and technological solutions is British versus French employment of squadrons. By the mid-1700s, as mentioned, Britain maintained permanent squadrons overseas, while France sent out annual squadrons. British warships would stay at sea and on station for longer periods than did French ships, which led Britain to emphasize key areas of research and innovation that France did not. For example, given its vessels' longer passage than the French to Atlantic stations and more frequent voyages to the Pacific, Britain led the way in research to combat scurvy, which typically set in after six weeks at sea without fresh victuals.²⁶

This extended sea time led British constructors to evolve heavier framing and reinforced joints between the frames and hull planking, in order for ships to stand up to the long and arduous service. By comparison, the shipbuilding methods developed over time by French constructors incorporated smaller frames and relatively modest fastening of the transverse structure to the shell, resulting in a lighter structure. In the less strenuous deployments under the French flag, the strength afforded by these practices was entirely adequate, and in fact the lighter French ships would have (all else being equal) a small speed advantage compared with heavier British ships, which also helped with their "hit-and-run" tactics. But when French ships were captured and taken into service under the British flag, naval officers would complain to the constructors that the lighter structure would eventually lose rigidity in the connections, causing the entire frame to flex, which would result in bending of the keel and greater leakage through the loosened planking.²⁷ Some of these differences in construction were due to the differing logistics of timber supply, as each navy strove to increase the inventory of wood and make the best use of the types and quantities that became

available.²⁸ But neither system was inherently superior, as each had evolved to suit the operational needs of its own navy.

The example of copper sheathing is also telling. The British navy instated coppering in 1761 as a means of defeating shipworms that ate through wooden hulls. It was quickly found to greatly reduce fouling (copper is poisonous to marine life), but problems developed with the electrolytic action caused by the use of iron bolts to fasten the copper plates to the hull. After a series of fits and starts to analyze the problem and develop the proper means of fastening, coppering became standard practice for British warships after 1784. This had the important effect of allowing them to stay on station for much longer before finding a harbor where the hull could be scraped; this effectively multiplied the military capability of an existing naval force without requiring additional ships. The French and other navies observed the British experience with caution before employing it themselves, and even then did not regard it with the same importance as the British navy.²⁹ The reduction in fouling also led to an increase in the average speed of a sailing ship over its life, to a much greater degree than any potential gains from improvements in hydrodynamic theory.

The Role of Ship Theory

During this era, ship theory played a minor but sometimes critical role in the coevolution of doctrine and technology. For example, in order to ensure that gun ports were high enough above the water, many constructors began calculating the displacement of the ship at various drafts in order to verify loading conditions. However, it was not constructors but naval administrators who believed in the importance of ship theory in design and pushed its development and use, as will be evident throughout this work. The writings of Colbert, who in the 1680s was one of the first to actively support this development, suggest that he believed a "scientific" approach to ship design could make each ship superior to those of its potential enemy, thus helping him to redress France's numerical imbalance with Britain and the Netherlands. This should be seen as part of his overall strategy of developing naval science (e.g., navigation and artillery) in order to gain advantage over enemy fleets.

More important, Colbert saw the use of theory as the basis for standardization by providing a common set of design principles to guide his constructors. While it is not clear that later naval administrators shared Colbert's faith in scientific naval architecture's ability to create faster and better ships, they certainly employed it as part of an increasing centralization and standardization of design and construction, and came to see it as a means of avoiding problems during construction and operation (e.g., the need to girdle ships—adding a layer of wood to the hull—to raise the freeboard to gun

ports or improve stability). They believed that the inclusion of theoretical calculations of stability, speed, and maneuvering gave them a measure of control over, and confidence in, both the constructors and the ships they built; the fact that constructors were required to perform these calculations meant that they had a firm grasp of the fundamentals of ship theory, and by ensuring that these calculations were carried out and reviewed by senior constructors, the chances of a major problem were, in their view, diminished.

Ship Models and Ship Plans

Naval architecture (i.e., the implementation of ship theory in design) could not have developed without accurately scaled two-dimensional plans of the hull on paper or parchment, from which constructors could precisely measure the lines in order to mathematically calculate hull surface areas and volumes. Yet it is not at all clear why ship plans were developed and incorporated into ship construction in the first place, when for many hundreds of years quite adequate methods were available to build ships directly on the ways. The most likely reason appears to be rooted in the desire by shipowners and naval administrators for a more “transparent” process (to use a modern business term), to better understand and control their constructors, and to ensure they were getting the ships they paid for. Naval administrators sought to do this through the use of both scale ship models and ship plans. However, two-dimensional drawings on parchment or paper were an efficient way of representing a ship, being less expensive, more transportable, and more accurate than three-dimensional wooden models, and ultimately became the method of choice to convey design information.³⁰

Ship Models

Scale models of ships served as both decoration and a means of conveying design information for teaching, construction, or “marketing” of a new ship (I do not include here models for testing, which are discussed in chapter 3). Ship models had certainly existed since the Egyptian pharaohs, although the surviving ones were generally votive. During the Song dynasty in China (960–1279), a standardization of ship types was achieved with the use of scale models, centrally manufactured and distributed to various shipyards along with a set of written instructions for the actual construction.³¹ The 1606 scale model of the Venetian state galley *Bucintoro* was probably made for decoration, while the 1634 model of the 100-gun *Sovereign of the Seas* was made by the ship’s constructor, Peter Pett, in a bid to have King Charles I approve the

construction of what would be the world's largest and most expensive warship. Probably the best-known systematic use of models was instated by the British navy around 1650. Various known as Navy Board, Admiralty Board, or simply Admiralty models, they usually showed external features above the waterline but were open below to show the framing.³²

Other navies soon followed suit, in some cases directly inspired by the British Navy Board example. In the 1660s and 1670s the Swedish navy, under the influence of the British constructors Francis Sheldon, Robert Turner, and Thomas Day, began requiring such models. Sheldon went to Denmark in the 1680s and introduced their systematic use to the Danish navy. In 1728, the Amsterdam dockyard hired the British constructors John May, Thomas Davis, and Charles Bentam, in part because they were able to use models to demonstrate their construction techniques to the Amsterdam Admiralty Board.³³ Ship models appear to have come into common use in Spain during the mid-1700s, and in Venice by 1775. In France, Navy Minister Colbert required floating models to be built under his 1673 regulation; but, as described in chapter 2, this turned out to be a failed experiment.

Models of the type required by the British Navy Board (figure 1.1) probably took a long time to build and were quite expensive, and the more elaborate models may have

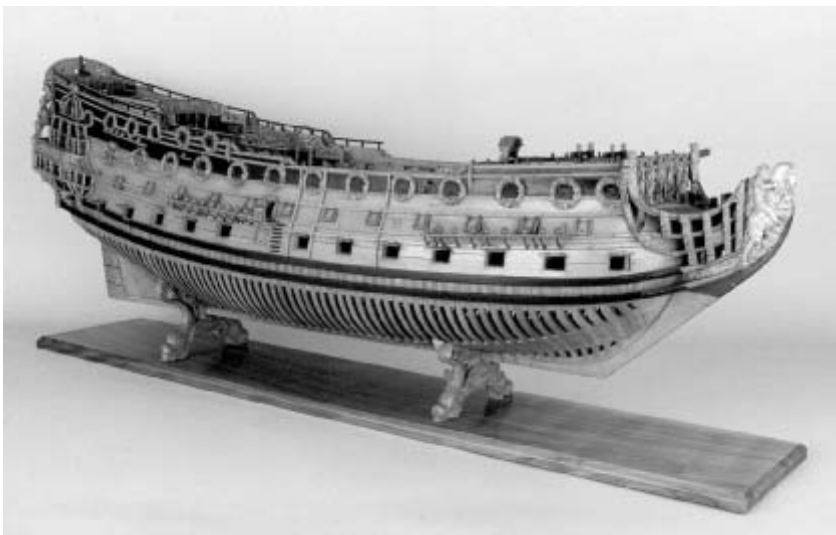


Figure 1.1

British Navy Board model of 100-gun H.M.S. *Britannia* (ca. 1677). Credit: U.S. Naval Academy Museum.

been built almost simultaneously with the ship. In many cases it is not clear that they represented as-built ships; their origins and purpose are shrouded in mystery.³⁴ It is doubtful they served as design templates; the frames could not be easily dismantled to make measurements, and in any event this process would probably have involved their transfer to paper in order to be scaled to full size, as would be done in the nineteenth century with “lift” half-hull models.³⁵ The models themselves were quite fragile, and would not have been carried around the dockyard to verify construction. The most likely purpose for these models, then (apart from decoration), was not so much to serve as design templates as to allow the administrators and constructors to visualize the details of the construction. In short, they served the increasing desire by naval administrations to better understand ship design and construction, so as to have a more informed oversight over their constructors.³⁶ The other facet of this standardization and control was the institution of ship plans.

Ship Plans

The original techniques for drawing plans on paper and parchment essentially reproduced, at small scale and at full scale the methods that constructors used when building directly on the floor of the molding loft or on the ground of the dockyard. These full-scale drawings were done using straightedges, compasses, and right triangles to establish reference points, with frame shapes generally composed of circular sections fitted together using a chalk swung in an arc at the end of a string. Typically, this process was first done for the midship section, called the master frame. Once the shape was drawn, the wood frame would then be hewn or fitted up in sections to the outline. Constructors would subsequently use various proportional rules to control the size and shape of intermediate transverse frames, a technique sometimes referred to by the generic name “whole-moulding”, although in fact there were many similar techniques employed around Europe.³⁷ The control of the overall fore-and-aft shape was often accomplished by using relatively light wood battens (ribbands) stretched between the transverse frames erected on the keel. Figure 1.2 is a schematic representation of the master frame, intermediate frames, and ribbands. The fitting up of other frames, stem and stern sections, and the hull planking would require additional control techniques. There were almost as many variations of these methods as there were shipyards, and as top constructors from one country were routinely hired away from their home shipyards by better offers from other nations, those techniques evolved and spread across Europe.³⁸

Ship plans did not start out as construction templates, but that is what they evolved into. The first known ship plans were parts of shipbuilding treatises, which from their

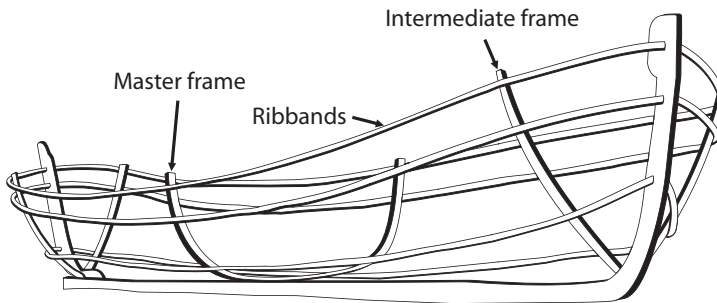


Figure 1.2

Schematic representation of master frame, intermediate frame, and ribbands. (After Damianidis, "Methods Used to Control the Form of Vessels" [1998], p. 218).

earliest appearance had drawings of midship sections and longitudinal sketches of the hull. The plans in these treatises were not always drawn to scale, so they were often accompanied by detailed instructions on how to actually trace out the frames and lines. Since the treatises were generally intended for instructional use or as general guides, they often showed plans of existing ships as examples, a common practice through the present day. For example, Mathew Baker's incomplete treatise from 1570, *Fragments of Ancient English Shipwrightry*, contained drawings of ships he and his father had built twenty to thirty years earlier.³⁹

Certainly by the early 1600s some constructors were drawing scaled ship plans as construction templates for their own use, Anthony Deane of Britain (active 1660–1690) being the best known. However, at that time most constructors continued to work directly at full scale. Naval administrators began requiring scaled ship plans at roughly the same time that they began requesting scale models. For example, the earliest systematic series of British ship plans were the drawings of William Keltridge, begun in 1680, only a few years after Navy Board models came into common use. The expatriate British constructors Francis Sheldon, John May, Thomas Davis, and Charles Bentam, who had brought models to Denmark, Sweden, and the Netherlands, also introduced the systematic use of ship plans to those navies. In Spain and Venice, the systematic use of plans began earlier than did the use of models. The director of Spanish construction, Antonio de Gaztañeta e Iturrizalza, was the first to regularly draw ship plans, starting in 1712, and in Venice, the hydraulics engineer and navy "consultant" Giovanni Poleni drew accurate plans of the 64-gun *San Carlo Borromeo* in the 1760s, when the Venetian navy decided to adopt it as the standard type for all ships of the first rate.⁴⁰

Given the fact that in each navy, scale models and ship plans came into common use roughly simultaneously, it would appear that naval administrators required them for two different but related purposes. Scale models were expensive and time-consuming, and may have been completed well after actual construction had begun. But even with scale models at their offices, administrators could not ensure that what was being built at the dockyard matched what the constructor had conceived and what they had paid for. Ship plans offered the administrators a means of standardization and control by giving the constructors a relatively inexpensive and quickly produced template to follow. In the first place, it was relatively straightforward for constructors to measure the lines and scale them up to full size; second, plans were transportable from a central bureau to and around the shipyard, as shown in Pierre-Quentin Chedel's somewhat fanciful woodcut from Bouguer's *Traité du navire* in figure 1.3. Later, a third advantage would be realized—plans could be repeatedly retraced and used in any shipyard, allowing for a truly standardized series of ships.

The level of detail in ship plans evolved during the late 1600s and early 1700s. In many cases, more attention was given to the bow and stern ornamentation and decoration for the officers' suites than to the actual lines for the hull.⁴¹ By the mid-1700s, however, most navies had developed a standard presentation of the ship, still in use

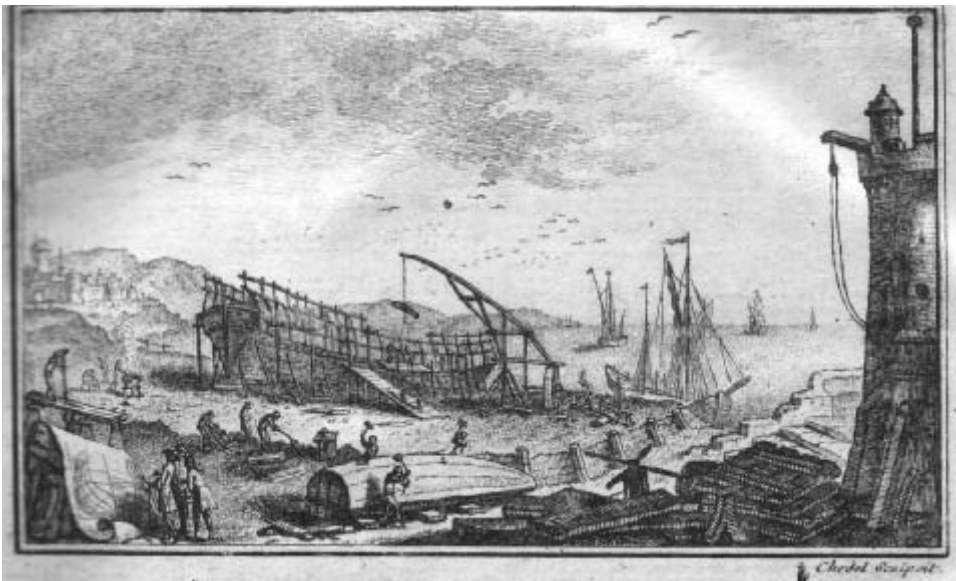


Figure 1.3

Constructors with drawings in a dockyard. (Bouguer, *Traité du navire* [1746], p. 1).

today, in three related orthogonal views: the profile or sheer plan of the hull at the top (usually without any buttock lines in that era); below that, the waterlines plan; and finally the body plan, set to one side of the profile, which is split so the left side shows the stern frames and right side shows the bow frames. Figure 1.4 shows an example for a French ship from 1739. The methods used by constructors to accurately represent complex curves in several planes were the most sophisticated graphical techniques in Europe until the descriptive geometry theorized by the French mathematician Gaspard Monge at the end of the century.⁴²

The methods of drawing frames and lines were refined over time, as instruments such as mechanical splines and rigid curves came into practical usage.⁴³ Figure 1.5 shows some of the drawing instruments used by early constructors. Of equal importance were the mathematical techniques that constructors began to use to help them better define the designs.

Mathematics and Ship Plans

Two-dimensional figures, especially symmetrical forms such as ships, immediately lent themselves to geometrical and mathematical analysis, a point not lost on early constructors. The first applications involved the substitution of arithmetical calculations for the geometrical devices that constructors used to develop the hull lines. For example, instead of using geometrically derived curves to develop proportionally larger or smaller frames, in the 1570s the British constructor Mathew Baker would instead calculate the proportions using fractions and cube roots, and also used these techniques to calculate hold volumes for cargo tonnage. While in theory this would be more accurate than the purely geometrical method, the frequent arithmetical errors made it quite problematic in practice. To this end, in 1615 Baker's colleague John Wells began employing logarithms in the calculations, only a year after their invention by the British mathematician John Napier.⁴⁴

By the early 1600s, at least some constructors were regularly using ship plans in their day-to-day work, which allowed them to calculate hull volumes using those mathematical techniques in order to estimate load waterlines. As described in chapter 4, this was originally driven by the need to ensure adequate freeboard of gun ports above the water, but would become a key element in the development and adoption of stability calculations in the mid-1700s. These calculations would not have been possible without the institutional use of ship plans.

Hull shapes also became the subject of mathematical analysis and manipulation, though rarely by constructors themselves, who saw no advantage to forms achieved only through complicated equations that they frequently could not understand. As

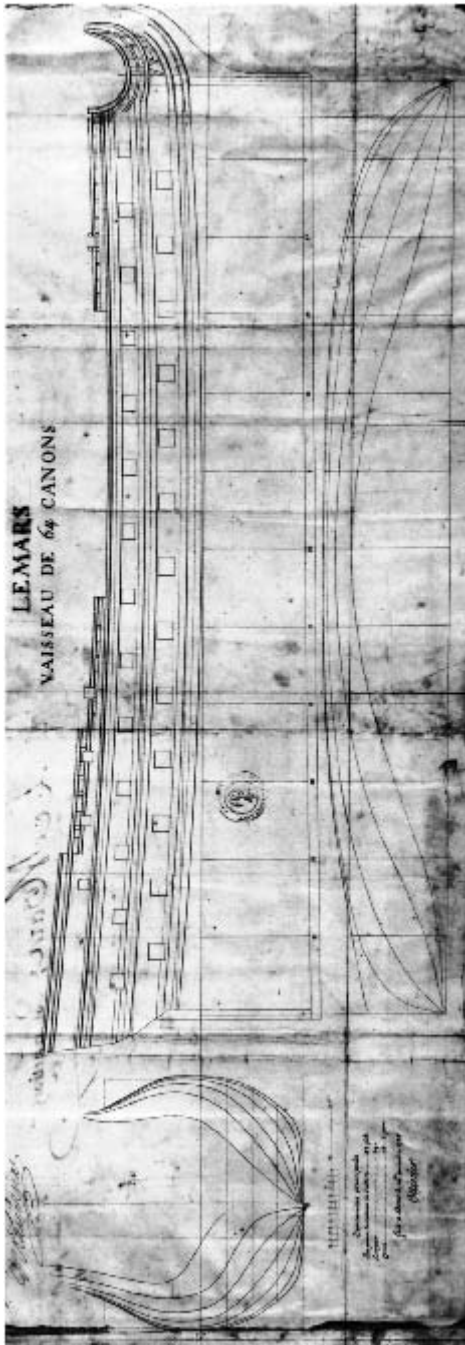


Figure 1.4

Plans for 64-gun *Mars*, showing standard three views of hull, by Blaise Ollivier (1739). Credit: Musée Nationale de la Marine, Paris (plan B9c/28446, photo 177968).

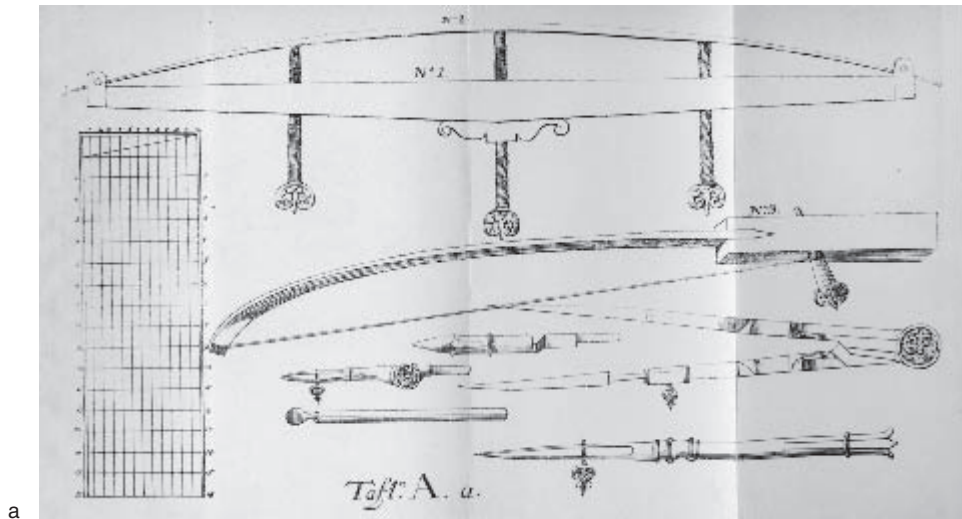


Figure 1.5

Top: Ship drawing instruments: adjustable splines, battens, bows, pens. (Rålamb, *Skeps byggerij eller adelig öfnings tionde tom* [1691], plate A). Credit: Cushing Library, Texas A&M University. Bottom: Portrait of Fredrik Henrik af Chapman holding ship's curve. (D. G. Harris, *F.H. Chapman: The First Naval Architect* [1989], p. 2). Credit: Conway Maritime Press.

will be discussed extensively in chapter 2, the French engineer Bernard Renau d'Elizagaray would base an entire theory of ship design on the use of elliptical hull forms, which almost no other constructor ever made use of. It did, however, pave the way for his 1689 book *Théorie de la manoeuvre des vaisseaux* (Theory of the Maneuvering of Vessels), the first treatise of naval architecture.

Shipbuilding Treatises

Renau's book, in which mathematical theory was used to predict a ship's performance, was a distinct break from traditional shipbuilding treatises that gave practical rules for design and construction. However, it received a good reception because it found a well-prepared audience. By 1689, when Renau's work was published, shipbuilding treatises were the accepted means of conveying ship design knowledge within professional circles. In addition to the published works available, most European navies had sponsored the writing of manuscript treatises that were widely circulated among administrators and constructors. By then these treatises were, for the most part, thoughtfully laid out and written in technical but comprehensible language. Of course, these works had evolved for 250 years; the first treatises were hardly so clear and logical.⁴⁵

The earliest known treatise that described shipbuilding practice was a manuscript dating from 1434/1444, written by a Venetian seaman known only as Michael of Rhodes. It was a general work of maritime scholarship, setting on paper Michael's accumulated wisdom on mathematics, navigation, astronomy, and shipbuilding, the latter making up only a quarter of the entire text. Though never published, it evidently was widely circulated, and parts of it were copied into other shipbuilding treatises, such as *Fabrica di galere* (Building Galleys, circa 1500), and *Arte di far vaselli* (Art of Making Vessels, circa 1550) by Theodoro de Nicolo.⁴⁶

For the most part, the earliest treatises (i.e., before 1600) were written in Italian (specifically in the Venetian dialect), were never published, and appear to have been the personal accounts of constructors, usually describing the design of oared galleys. They were evidently aimed at other constructors, not at apprentices or administrators. They were often dry reading, repeating on paper what were probably oral traditions for proportions and measurements of ships, without providing any underlying explanations. It is not clear just why they were written; most took a haphazard notebook form rather than a clear outline, and some treatises have the appearance of an omnium-gatherum of a person's accumulated life wisdom on many subjects. The latter was true even for non-Italian treatises; Mathew Baker's 1570 treatise, *Fragments of*

Ancient English Shipwrihty, was, as the title implies, quite incomplete and disjointed, having been added to by Baker's colleague John Wells.⁴⁷

The first published work on shipbuilding was printed not in Europe but in the Americas. Diego García de Palacio was not a constructor but a Spanish-born government official in the viceroyalty of Mexico. In 1587 he published *Instrucion nauthica, para el buen uso y regimiento de las naos su traça, y gobierno conforme à la altura de México* (Nautical Instruction, for the Good Use and Management of Ships, Their Design, and Conduct in Accordance with the Latitude of Mexico).⁴⁸ Written as a dialogue between two men, the book was really a compendium of nautical matters for Latin American waters, including astronomy, weather prediction, and chartmaking. Only a quarter of the book was actually devoted to ship construction, mostly concerned with masts and rigging, with fewer than ten pages referring to hull construction. Yet *Instrucción náutica* (in its modern Spanish spelling) marked a distinct change in the style of shipbuilding treatises. It was not a personal account of years of experience aimed at other constructors, but a government-sponsored document by an outsider to the field, aimed at disseminating the knowledge to a wider audience that would have included apprentices and naval administrators. In addition to listing proportions and measures of the hull and rigging to follow during construction, it gave some explanations of why certain calculations were made, which gave it a more instructional quality.⁴⁹

Many shipbuilding treatises written in the 1600s treated the subject as one branch of the wider field of architecture, and (as briefly described in the preface) began to employ the term "naval architecture." The idea that naval architecture meant, literally, an "architecture of the sea" may have begun with the Italian artist Leon Battista Alberti, who around 1450 wrote "*Navis*" (The Ship), a now-lost unpublished manuscript that paralleled his published book *De Re Aedifactoria* (On the Art of Building), one of the first great treatises on architectural theory. Vettor Fausto, a Venetian professor who designed some rowed galleys based on classical texts, certainly had this concept in mind when he argued in 1530 that even though terrestrial architecture, with its straight lines, was hard to learn, that of the sea was even harder, as it contained only curves.⁵⁰ The British mathematician Thomas Digges also alluded to this idea in 1579 in an unfulfilled promise to write a treatise of "Architecture Nautical."⁵¹

This idea was firmly stated around 1610 by the Portuguese mathematician and engineer João Baptista Lavanha in his unpublished "*Livro primeiro de arquitectura naval*" (First Book of Naval Architecture), the first treatise to define and use the term "naval architecture."⁵² Lavanha consciously used the well-known text of the Roman architect Marcus Vitruvius Pollio to outline his theories, and was among the first to identify scale drawings as the starting point for ship design. Like *Instrucción náutica*, *Livro*

primeiro was a work written by a scholar and not a constructor, providing detailed explanations of construction practices that evidently were intended for a wide readership. The first published work to use the term “naval architecture,” *Architectura Navalis* (Naval Architecture), was written in 1629 by the German architect Joseph Furttenbach as part of a six-volume series on architecture that included military architecture, civilian architecture, and recreational architecture. In other words, Furttenbach placed ship design squarely in the same camp as other types of architecture, although his actual intention was to recommend that the German cities build specific types of ships by describing in detail how they were constructed.⁵³

By the late 1600s, shipbuilding treatises were being written in almost every European nation, some published and others remaining in manuscript form. In most cases they were authorized and paid for by someone in the navy administration, and were dedicated to that person, with the clear intent of ensuring a wide dissemination of this knowledge. In certain cases, the authors were scholars unconnected with ship construction. For example, in 1643 the French hydrographer Georges Fournier included a substantial discourse on naval architecture in his widely read and influential book *Hydrographie* (Hydrography).⁵⁴ In the Netherlands in 1671, the mayor of Amsterdam, Nicolaes Witsen, wrote *Aeloude en hedendaegsche scheeps-bouw en bestier* (Ancient and Modern Shipbuilding and Handling), a hodgepodge of observations on historical ships and current shipbuilding methods that, although chaotic and difficult to read, became one of the most widely sought-after shipbuilding texts in Europe.⁵⁵ In other cases, treatises were commissioned specifically for navy use, to provide some standardization for shipbuilding practices or general instruction. For example, in 1670 the British constructor Anthony Deane was requested by Secretary of the Admiralty Samuel Pepys to write down his ship design methods, which became known as his “Doctrine of Naval Architecture,” and, though never published, was widely circulated within the Admiralty.⁵⁶ In France, the constructor Charles Dassié published *L'Architecture navale* (Naval architecture) in 1677, which provided French administrators and constructors with specific design instructions that followed the regulations for sailing warships and galleys recently codified by Colbert.⁵⁷ In Sweden, *Adelig öfning* (Exercises for Young Noblemen), an encyclopedia of practical knowledge on mathematics, geography, fortifications, and such by Åke Classon Rålamb, included a volume titled *Skeps byggerij* (Shipbuilding), published in 1691, which contained descriptions of ship construction as well as drawing techniques.⁵⁸

The advent of theoretical works of naval architecture, such as Paul Hoste's 1697 *Théorie de la construction des vaisseaux* (Theory of the Construction of Vessels) and, most important, Bouguer's 1746 *Traité du navire* (Treatise of the Ship), did little to slow

the publication of practical treatises on shipbuilding through the end of the 1700s. In Spain, the naval officer Juan José Navarro de Viana y Búfalo, marquis of Victoria, took 37 years (1724–1761) to write—but not publish—the “Album del marqués de Victoria” (Album of the marquis of Victoria), a remarkable illustrated album of shipbuilding in the form of a dictionary intended for the Navy Guards.⁵⁹ In the Netherlands, two shipbuilding treatises were published in 1757 that explained Dutch shipbuilding methods as a defense against unfavorable comparisons with imported British methods: *Verhandeling van den Hollandschen scheepsbouw* (Treatise on Dutch Shipbuilding), by Leendert van Zwiendregt, and *Korte verhandeling van den Nederlandsche scheepsbouw* (Short Treatise on Dutch Shipbuilding), by Willem Udemans Junior.⁶⁰ In Sweden, Fredrik Henrik af Chapman, steeped in ship theory, first published his *Architectura Navalis Mercatoria* (Merchant Naval Architecture) in 1768 as a set of construction lines without any recourse to theoretical naval architecture. Some of the first textbooks of naval architecture grafted ship theory onto how-to-build texts (beginning with Duhamel du Monceau’s 1752 *Éléments de l’architecture navale*), but works of theory and practice eventually grew apart throughout the nineteenth and twentieth centuries. Today, the U.S. Society of Naval Architects and Marine Engineers publishes two separate works, *Ship Design and Construction*, which is entirely practical, and *Principles of Naval Architecture*, which is completely theoretical.⁶¹

By the late 1600s, then, naval administrators in many nations were already moving toward stronger control of ship design and construction. They were demanding that constructors build scale models and draw ship plans in order to better understand the product, and to ensure that what they saw in their offices was actually being built. They were authorizing and paying for shipbuilding treatises, ensuring that knowledge was made widely available and not kept within the walls of the dockyard. So when engineers and scientists made the first essays into developing mathematical theory for ships, naval administrators such as Jean-Baptiste Colbert quickly saw it as the next logical step toward greater control over their constructors and for standardization of the ship design process.

2 Deriving the *Dérive*

The first extended investigation into theoretical naval architecture began with a question any child might ask—How can a boat sail against the wind? But when the question came from the king of France, it required a rather more extensive response than one might have given to a curious youngster. This chapter explores that first investigation, which was the problem of maneuvering and, more specifically, the *dérive*, the leeway (sideways drift) of a sailing ship. The response to the king would eventually escalate into the earliest and longest-running debate in naval architecture, which would take place within the growing number of learned societies, books, and journals that were the principal structures of the Scientific Revolution. Therefore, this chapter opens with an exploration of those structures, beginning with the Jesuits, before examining how Jean-Baptiste Colbert and an almost unknown engineer named Bernard Renau d'Elizagaray shaped this debate in the late 1600s. A quarter-century later, the work of Pierre Bouguer in extending this line of investigation to the masting of ships would bring him to prominence in the French Academy of Sciences and set the stage for his great synthesis of naval architecture.

Structures of the Scientific Revolution

Jesuit Beginnings

Iñigo López Oñaz de Loyola was certainly not thinking about science as he lay in his bed while his shattered leg slowly mended. He had been a foot soldier during the Spanish defense of Pamplona against the French in May 1521, when a cannonball passed between his legs, breaking his right tibia and tearing open his left calf. Recovering in his family castle from the operations that reset his leg bones, he found none of the tales of knighthood and chivalry that he so enjoyed, only some lives of Christian saints. He began to imagine himself as a sort of chivalric saint. Although his recovery left him with a lifelong limp, with a group of followers he made pilgrimages to

Jerusalem and Rome, where he took the name Ignatius. The ex-soldier would tell people that his group belonged to no religious order, but to the Company of Jesus (in Latin, *Societas Jesu*, abbreviated S.J.), a military connotation in which an army company was named after its captain, and which also marked the military mind-set and discipline of the Jesuits that Ignatius Loyola instilled.¹

The Jesuits, officially founded in 1540, were not like other Catholic orders. Neither monastic like the Benedictines, nor like the Franciscans, who took vows of poverty, the Jesuits were missionaries in the sense of actively working within their communities, which eventually extended around the globe. In cities and towns Jesuits opened colleges that taught classics and religion to middle- and upper- class boys between the ages of 10 and 14—the equivalent of the modern high school. At its peak, the global Jesuit educational system included over 850 colleges and universities that educated over 200,000 boys and men annually, including a significant number of the government officials, scientists, and mathematicians who would shape the Scientific Revolution, many of whom would themselves become Jesuit priests.

Education was central to Jesuit life, but as a means to greater spirituality and not as an end in itself. The colleges and universities taught the theology set down by the Dominican friar Thomas Aquinas, which incorporated the physics and metaphysics of Aristotle and the rudimentary geometry of Euclid. However, beginning with the tenure of the German mathematician Christoph Clavius at the College of Rome in the late 1500s, most Jesuit institutions had at least one mathematician or scientist, which was certainly desirable for attracting the kind of well-off families whose patronage helped keep the schools in business. Scientific learning became a hallmark of Jesuit education, but the ability of priests to research and publish was constrained by the need to keep within Church doctrine.

By the 1700s, the Jesuits had become the single greatest organization for scientific instruction in Europe, far surpassing Loyola's original vision. In France, for example, Jesuits taught sciences in 85 of 90 colleges, and mathematics at a number of universities. The mathematics chairs at the three academies (Brest, Rochefort, Toulon) of the Navy Guards, an elite corps of naval officers formed in 1670, were occupied by Jesuits, most famously by Paul Hoste, who wrote *Théorie de la construction des vaisseaux* (Theory of the Construction of Vessels), the first attempt at a synthesis of naval architecture. Jesuit colleges in France taught hydrography (essentially, navigation and piloting) before Colbert, in 1681, created hydrography schools under Jesuit control. Even the lay instructors were Jesuit-trained; Pierre Bouguer was schooled at the Jesuit college in Vannes.²

Another defining Jesuit trait was travel, a critical facet in the establishment of scientific discourse in Europe and abroad. To maintain control of its missionaries in Europe and abroad, the Jesuits had a highly centralized bureaucracy with orders flowing down from the Superior General at the Gesù basilica in Rome to his five assistancies in Europe, and then to the provinces and overseas. Mixed with the almost continuous flow of administrative reports were detailed field observations. Jesuits were trained to be careful observers and clear writers, and sent back reports on the local culture, natural history, and geography in order to better understand the societies in which they operated. This correspondence was systematically gathered and disseminated, not only internally but also for publication in journals. This model became a central feature of the Republic of Letters, and the correspondence of its key figures (Leibniz, Newton, Euler, etc.) invariably included a significant number of Jesuits.³

But this correspondence was not always amicable, for the Jesuits had many enemies, not only because of their theology but also because of a widespread perception of political influence and partisanship. This was true even in scientific circles. In Britain, the Royal Society was openly hostile to the Jesuits and refused to make use of their far-flung networks' reports on natural history. The Jesuits' relationship with the French Academy of Sciences was rather more complicated; though they were nominally excluded from membership, their correspondence was nevertheless often published in the Academy *Memoirs*. Jesuits were also often at loggerheads with government officials, some of whom openly called for their suppression.⁴ All that was needed was a catalyst.

Just before ten o'clock in the morning on 1 November 1755, as the population of Lisbon was attending All Saints Day mass, a massive offshore earthquake shook the city for seven minutes. The water drained out of the harbor and returned as a 15-meter wave, followed by two aftershocks. By noon, 15,000 people were dead and the city was reduced to rubble. It was the most devastating natural disaster in European history, and provoked a wide range of reactions across the continent. For the French playwright Voltaire, it was a source of bitter irony that inspired him to write the play *Candide*, which satirized the notion that "everything happens for the best." For the Portuguese Jesuits, it was proof that God was unhappy with the people of Lisbon. And for Prime Minister Sebastian Joseph Carvalho, marquis of Pombal, who disliked the Jesuits for their opposition to his colonization of Brazil, the popular revulsion at their moralization was the catalyst that he needed to make the case for their expulsion, which was granted in 1759. Beginning with that event, the earthquake that leveled Lisbon would eventually level the Society of Jesus.⁵ Once Portugal took the first step,

other nations quickly followed suit, so that by 1773 the Society was formally dissolved, and would not be reinstated until 1814. Their suppression left a gaping hole in the European educational system, not to mention in other areas, such as the French schools of hydrography, which would not be fully repaired until well into the next century.

Journals

The Jesuit field reports that circulated throughout the Society were just one example of the range of erudite correspondence that gave the name “Republic of Letters” to the widely dispersed scientific community of the seventeenth and eighteenth centuries. This was facilitated by the advent of regular postal services to replace expensive couriers. Scientific discoveries often were initially transmitted by means of such letters, before being printed in pamphlets or books. Certain individuals acted as clearinghouses for such discoveries, the best-known being the (Jesuit-trained) French priest Marin Mersenne. He exchanged letters with dozens of scientists from across Europe and overseas, and thus knew who was working on which topics; if he received word of an important advance in an area, he would retransmit it to the right people who were working on the same problem.

These letters often became the basis of contributions to learned journals. The first such journal to be published on a systematic basis was the *Journal des sçavans* (Journal of Scholars), begun in 1665. After an initial reorganization to address Jesuit concerns, the journal soon became a principal venue for scientists to announce discoveries, especially the members of the French Academy of Sciences, which had no official publication until 1700. In 1701 the *Journal des sçavans* was again reorganized under an editorial board, and continued to be the premier scientific journal in Europe until its suspension in 1792.⁶

Other scientific journals were quickly created on this model—from 1600 to 1800, over 1,800 journal titles appeared in cities from Paris to Amsterdam to Leipzig. Many were regional or specialized in one domain (e.g., medicine), but a large number provided wide-ranging accounts for the general reader, including extensive reviews of books. Some publications lasted only a few years; *Histoire des ouvrages des sçavans* (History of the Works of Scholars) in Rotterdam was printed only from 1687 to 1704, and *Bibliothèque universelle et historique* (Universal and Historic Library) was published in Amsterdam by Jean Le Clerc only from 1686 until 1693. *Acta eruditorum* (Transactions of the Learned), founded in 1682 in Leipzig, was one of the few scholarly journals to be published exclusively in Latin, then still the principal language of the exact sciences. It had a wide readership and attracted contributions from scientists and

mathematicians such as Leibniz and the Bernoullis. By contrast, the *Journal de Trévoux*, also known as *Mémoires pour l'histoire des sciences et des beaux arts* (Memoirs for the History of the Sciences and Arts), was begun in 1701 by a group of Jesuit priests as a broad review of theology, news, and the arts, with occasional scientific articles printed as “extracts.” Thus, authors had a wide variety of outlets for their publications. If they were aiming at a specific group of mathematicians, they might publish in *Acta eruditorum*, whereas a publication in *Journal de Trévoux* reached a wider, often nonscientific audience.⁷

Books

The rapid growth of journals owed much of its success to book reviews concurrent with the explosion of book publishing across Europe. In 1700, book fairs in Paris, Leipzig, and Frankfurt were the main source of income for the book trade, as transport problems (bad roads, high tolls, etc.) limited direct sales, but by the 1750s the European infrastructure had improved to the point where direct sales were more common. Publishers and booksellers, then as now, kept a close eye on the market; books in Latin did not sell very well by the mid-1700s, and English by that time was overtaking French as the preferred language.

Booksellers sometimes printed their own books as well as selling the books of other publishers, and they were the vital link in their marketing and sales. In some cases the publisher would assemble and bind the printed sheets before shipping, while in others they would be sold in quarto or in octavo (respectively, a sheet of four or eight pages), which would have to be cut apart, trimmed, assembled, and bound by the bookseller. Along the way, the books or untrimmed sheets would be carried by horse-drawn cart along roads or by barge that made stops at customhouses and warehouses. Every major city had a large bookseller (e.g., Panckoucke and Jombert in Paris, Esslinger in Frankfurt), and they had agents who went into the towns and villages to market to individual buyers. Booksellers would typically contract with the publishers for an initial run (often 500 to 1,000 copies), the individual buyers would pay the booksellers, and the booksellers would pay the publishers. In some cases the booksellers would hold one edition for decades before it was completely sold. The prices of books varied by their size and the market. For example, Bouguer's short *De la Mâturation des vaisseaux* (On the Mastings of Vessels) sold for 6 *livres tournois* (about \$40 in 2002). Bossut's very specialized *Traité d'hydrodynamique* (Treatise on Hydrodynamics) brought 10 *livres* (\$68), and Bouguer's massive *Traité du navire* (Treatise of the Ship) sold for 15 *livres* (\$100). The complete edition of the first *Encyclopédie* (Encyclopedia) by Diderot and D'Alembert fetched from 225 to 980 *livres* (\$1,500 to \$6,600).⁸

Although each scientist and engineer had his own professional library (there were no public lending libraries), the market for scientific and technical books was comparatively small, and publishers were naturally reluctant to publish new works without the promise of a buying public. In many cases, authors would look to wealthy patrons, to whom the book was dedicated, but this was not always possible. The Swiss mathematician Leonhard Euler complained that he could not find a patron or a publisher for his *Theoria Motus Corporum Solidorum* (Theory of the Motion of Rigid Bodies), now considered a masterwork of rational mechanics, for almost six years; and when A. E. Rose of Rostock finally agreed, Euler was not allowed any complimentary copies for his friends, as “he has had only 500 copies printed, and by all appearances he will not sell 100 of them.”⁹

In Russia, the problem of finance was often gotten around by the use of the Imperial Academy of Sciences Press, which took over the Saint Petersburg Press in 1727 and soon became the largest publisher in Russia, accounting for half the books printed there. Scientists working at the Academy were virtually guaranteed publication of their work, although there were often long delays because the financial side of the Academy did not always agree with the scholastic side; Euler waited seven years for publication of his *Scientia Navalis* (Naval Science), which occurred after he had left Russia to work at the Berlin Academy of Sciences.¹⁰ In France, scientists and engineers would often submit their works to the Academy of Sciences for approval, which gave them access to royal funding (e.g., through the minister of the navy for maritime books). These works appeared with the legend *avec approbation et privilège du Roi* (with the approval and license of the king). In turn, the government granted certain publishers near-exclusive rights for both publication and sales.

At the center of naval architecture publications were three generations of the Jombert family. Claude Jombert got his start in this field in 1720 when he took over the printing and selling of engineering works from his neighbor Étienne Michallet, who wanted to specialize in religious books.¹¹ He intended his son Charles-Antoine to enter the Corps du Génie (Corps of Engineers), for military fortification and artillery specialists, but at Claude's death in 1735 Charles-Antoine left that school to take over the publishing business. With his father's existing collection of engineering works, coupled with his own training and connections in the military world, it was not long before Charles-Antoine Jombert was given the royal privilege “Bookseller to the King for Artillery and Engineering.” From 1739 to 1775, his publishing was closely interwoven with the work of his childhood friend Charles-Nicholas Cochin, an engraver at the Royal Academy of Painting and Sculpture, whose detailed works (along with those of Pierre-Quentin Chedel) graced the pages of Jombert's books, including the

technical illustrations and the woodcuts that adorn *Traité du navire*. In 1769, Charles-Antoine's son Claude-Antoine began taking over the business, although the father kept a hand in. Jombert's bookstore was a place where scholars congregated to peruse books and exchange news, and his business was one of the most prolific in Europe. The Jombert family published, in addition to several of Bouguer's works, Duhamel du Monceau's textbook *Éléments de l'architecture navale* (Elements of Naval Architecture) and the revised and unauthorized version of Euler's *Théorie complète de la construction et de la manoeuvre des vaisseaux* (Complete Theory of the Construction and Maneuvering of Vessels). A change in the copyright laws in 1777 took away Jombert's royal privilege, and in 1782 Claude-Antoine went bankrupt. On the eve of the French Revolution in 1789, he shut the doors of the business forever.¹²

Academies and Societies

Just as the scientific journals of the mid-1600s were spawned from the private correspondence of scientists, so the scientific academies and societies that arose at the same time had their antecedents in informal salons and meetings. In the 1640s, two separate groups of scientists—one in Britain, the other in France—began convening on a regular basis to discuss their experiments and observations. In Britain, the “Invisible College,” which met in London and Oxford, included notables such as Robert Boyle and John Wallis. In France, the “Academy of Montmor” met in the Paris home of Henri Louis Habert de Montmor and included Gilles Personne de Roberval and Christiaan Huygens. The two groups exchanged visits on occasion.¹³

In Britain, the members of the Invisible College organized into the formal Royal Society in 1662, and in 1665 the *Philosophical Transactions of the Royal Society* became the first de facto society proceedings in Europe. From the start, it was “Royal” in name only, as no government funding came its way. The members, who could be termed “wealthy amateurs,” paid membership dues that covered the costs of publications and conducted experiments in their own laboratories—for instance, William Petty, a doctor and economist, in the 1660s conducted trials of a novel catamaran hull. In many cases (such as Petty's), the results were read before the Royal Society but never published in the *Transactions*, which rather limited their utility.¹⁴

The powerhouse of European science was the French Academy of Sciences, and like so many French institutions of the age, it was the creation of Finance Minister Jean-Baptiste Colbert, who in 1666 granted a royal charter to members of the Montmor Academy.¹⁵ Colbert intended the Academy of Sciences, like the Royal Society, to provide sound technical advice on problems of the day. However, it was far different from the British organization in both its structure and its span of control. It was

government-funded and met in the king's modest library until 1679, when it moved to the sumptuous Louvre Palace, on the first floor of the present-day Sully Wing, in the western hallway in the present-day room 33, salle Henri II (see figure 6.3).¹⁶ Its members were paid a stipend to conduct research, and Colbert spared no expense to attract eminent scientists from abroad, such as Christiaan Huygens from the Netherlands, Giovanni Domenico Cassini from Genoa, and Ole Rømer from Denmark. The Academy was also charged with reviewing machines and inventions for royal patents, and manuscripts for copyright and publication. At first, news from the Academy was printed in such venues as the *Journal des sçavans*, but after a major reorganization in 1699, it published its own proceedings under the title *Histoire et mémoires de l'Académie Royale des Sciences de Paris* (History and Memoirs of the Royal Academy of Sciences of Paris).

Academy sessions were held twice a week, and typically involved a member reading his memoir (sometimes this could take several sessions); unfortunately, there was no large blackboard on which to write equations or figures, and members were often left in the dark as to the actual content of, say, a mathematical treatise. A letter from a correspondent from abroad might be read aloud. Inventions or manuscripts were introduced for approval, and the assembly appointed a commission to review them. Every year the topic for a contest, called the Rouillé Prize, was announced, and a specially appointed committee would examine the entries. The contents of the proceedings, often years late, were debated and corrected. There were especially lively debates on vortices, gravity, and the Earth's shape, which led to the geodesic missions to Peru and Lapland.¹⁷

The Academy had especially close ties with the navy; both Colbert and his successor as minister of the navy, the count of Maurepas, were officers of the Academy. Bouguer and others regularly published memoirs on ship theory in the proceedings, and of the 80 Rouillé Prizes proposed between 1720 and 1792, almost a quarter concerned fluid mechanics and maritime subjects. In 1752, after several years of informal meetings, the navy created the Académie de Marine (Academy of Navy) at Brest (later "Royal" Academy), which included such figures as Bouguer and Duhamel du Monceau. It was the only learned society in Europe dedicated to naval matters. Although endowed with an extensive library and having official ties with the Academy of Sciences, the Royal Academy of Navy produced little work of real importance, only one volume of memoirs in 1773 that received almost no attention outside France.¹⁸

Other scientific academies formed on the heels of the Academy of Sciences and the Royal Society, often by poaching their members. The Royal Academy of Science and Literature of Berlin, or simply the Berlin Academy, was formed in 1746 by Friedrich

II, who wanted to bring Prussia closer to the French model of state. The Berlin Academy published its memoirs not in German but in French, and Friedrich brought Pierre-Louis Moreau de Maupertuis from France to be its president. Friedrich had already persuaded Leonhard Euler to come from Saint Petersburg in 1741, and with other émigré scientists the Academy soon attained first-rank status. Euler's three great memoirs that would form the cornerstone of hydrodynamics (discussed in chapter 3) would be published there, and Euler himself would later take over the presidency until he returned to Saint Petersburg in 1766. The Imperial Academy of Sciences of Saint Petersburg was an older establishment, created in 1724 by Czar Peter I just before his death. Like the Berlin Academy, it initially depended on foreign members to fill its ranks; between 1725 and 1742, three-quarters of its members were German-speaking, although its publications were in Latin. The Academy published Euler's *Scientia Navalis* as well as Daniel Bernoulli's early works on the stability and motions of floating bodies.¹⁹

The Royal Swedish Academy of Sciences was founded in 1739 on the heels of the Geodesic Mission to Lapland, in which the Swedish astronomer Anders Celsius participated and which helped further open Sweden to European scientific influence. From the start the Academy was intended to promote science in the nation, and consequently issued its publications in Swedish. This limited their circulation around Europe, but the Academy as a whole was very successful as a national resource. It counted as members the engineer Christopher Polhem and the astronomer Pehr Elvius, both of who presented memoirs on naval architecture. Moreover, the experienced naval constructors Gilbert Sheldon and Fredrik Henrik af Chapman presented important memoirs, those by Chapman on ship stability and resistance being of particular significance.²⁰

There were other scientific academies and societies in Europe, but few played any significant role in the development of naval architecture. The Royal Danish Academy of Sciences and Letters sponsored a prize on ship strength in 1775, which the Danish constructor Ernst Vilhelm Stibolt won the following year; his entry was eventually published as *Afhandling om skibes kiølbrækkelighed* (Treatise on Keelbreaking of Ships).²¹ In 1791, the Society for the Improvement of Naval Architecture was formed in Britain, and though it sponsored important research in hydrodynamics, it lasted less than a decade.²²

Dissemination of Naval Architecture Knowledge

Table 2.1 shows the pattern of dissemination of naval architecture knowledge in published works from 1680 to 1799. The venues covered are learned journals, the

Table 2.1

Dissemination of naval architecture knowledge, 1680–1799

	Journals	Academies	Treatises	Textbooks
1680–1689			Renau	
1690–1699	<i>B H H</i> <u>AAAAA</u>	F B	Hoste	
1700–1709	<u>AA</u>	F F B		
1710–1719	<i>T T</i>	B	Renau, Johann Bernoulli	
1720–1729		F F F F <i>P P P</i>		
1730–1739	<i>T T</i>	F F F <u>R R</u>	Pitot La Croix	
1740–1749	<i>T</i>	F F S S S S S	Bouguer <u>Euler</u> Savérien	
1750–1759		F F F F O <u>P P P P P</u>	Bouguer	Duhamel Murray Bourdé
1760–1769		F F F O S P P P P P P		
1770–1779		F F D O	Juan y Santacilia Chapman Euler, Bossut	Hennert Maitz de Goimpy Vial du Clairbois
1780–1789		S O O	Romme Du Buat Burgues, Stibolt	Vial du Clairbois Anonymous Vial du Clairbois
1790–1799		S B B I	Ducrest Chapman, Gay	

Journals: *B* = *Bibliothèque Universal*, *H* = *Histoire des Sçavans*, *A* = *Acta Eruditorum*, *T* = *Journal de Trévoux*.

Academies/Societies: F = France, P = Rouillé Prizes (France), B = Britain, D = Denmark, S = Sweden, R = Russia (St Petersburg), I = Improvement of Naval Architecture (London), O = Other.

Treatises and Textbooks: By author.

Latin texts underlined.

proceedings of academies and societies, treatises that provided original theories, and textbooks used principally for teaching. I have included only those works that were directly applicable to ship theory; for example, Daniel Bernoulli's pivotal book *Hydrodynamica* (Hydrodynamics) was a general work on fluid mechanics, and so does not appear.

Several patterns emerge:

- Latin effectively disappeared as a principal language of communication by 1750.
- Journal articles comprised a large proportion of the earliest works (1690–1720), centering on the debate over the *dérive* (described later in this chapter).
- From 1720 to 1770, a great number of memoirs appeared in academy and society proceedings, most notably of the French Academy of Sciences and in particular the Rouillé Prizes.
- Treatises flourished in 1720–1750 and again after 1770.
- Instructional textbooks such as Duhamel du Monceau's *Éléments de l'architecture navale* appeared almost immediately after the first treatises of Bouguer and Euler; many were intended for the French School of Maritime Engineering.²³ Similar textbooks appeared around Europe, though in many cases they seem to have been intended for private consumption, as there were few formal systems of naval architecture education outside France.²⁴ A massive effort to bring all naval architecture and other maritime knowledge into one place was completed in the *Encyclopédie méthodique: Marine* (Methodical Encyclopedia: Navy),²⁵ which treated the subject in far more depth than Diderot's *Encyclopédie*.

Each of the means of dissemination was a product of its times. In the late 1600s, many constructors were not literate, and so were not direct consumers of theoretical knowledge; it made sense to publish the few works in the pages of general journals that were circulated to a wider, literate audience. However, distribution was spotty, and unless one had subscriptions to all the journals and scrupulously read through each, it was hard to follow the train of events. By the early-to-mid-1700s, literacy was improving and constructors were becoming more exposed to scientific writings. The proceedings of academies and societies, fewer in number and narrower in scope than the journals, were somewhat better solutions, even if memoirs were often published years late. However, few constructors were full members of the academies and societies, and thus many could not access such information. These learned societies were still rather general-purpose, and the idea of a dedicated professional body was years away. In 1791, the short-lived Society for the Improvement of Naval Architecture was the

harbinger of the specialized engineering societies that would come to dominate the landscape in the 1800s.

Individual books (treatises) were a much better means to reach the growing audience that specialized in ship theory, as they contained information in one place, although the mathematics was frequently unintelligible to all but the most serious scientists. If the production run was small, books were often hard to find; Bouguer complained that he could not find a copy of Renau's important work *De la Théorie de la manoeuvre des vaisseaux* (On the Theory of the Maneuvering of Vessels).²⁶ Also, the prices of books often put them out of the reach of individual constructors.

The first truly effective solution to disseminating naval architecture knowledge evolved simultaneously with the formal educational system (discussed in chapter 6). Textbooks such as *Éléments de l'architecture navale* were made available to student constructors free of charge, and distilled the important information into practical usage that did not require extensive mathematics. Working constructors often used those texts in their day-to-day ship designs, and the fact that they had all learned from the same works meant that the design methods were more uniform between dockyards. Such uniformity of design and construction was the Holy Grail of naval administrators beginning with Colbert, though he would never see it in his lifetime.

Colbert, Renau, and the Search for a Theory of Construction

Herding Cats

Modern business schools teach managers to follow certain steps in order to reengineer their corporations: benchmark the competition, develop a set of best practices, get senior management onboard with the changes, and ensure follow-through on implementing those practices. Jean-Baptiste Colbert (figure 2.1) certainly understood and applied those principles, even if he did not call them by the same names, when he tried to overhaul French naval shipbuilding from 1670 to 1683. This reengineering effort was ultimately to no effect; he could not get his constructors to agree on and work to a common set of design principles, despite his best efforts. The reasons for this failure were complex, but ultimately came down to the fact that Colbert was trying to infuse new methods into an established group of professionals, rather than “grow” a completely new group trained from youth in those methods.

Colbert started his professional life as a merchant, but made good political connections early on with the future prime minister, the Italian cardinal Giulio Mazzarini (Jules Mazarin) that would lead to his rapid rise in power at the royal court. When he became intendant of finances in 1661, he set about putting France's economic affairs



Figure 2.1

Jean-Baptiste Colbert. Oil by Claude Lefebvre (1666), Châteaux de Versailles et de Trianon. Credit: Réunion des Musées Nationaux/Art Resources (New York).

in order so as to reduce the debt and attain a degree of self-sufficiency through mercantilism and heavy investment in roads and canals. He created the Academy of Sciences and the Paris observatory in order to provide scientific support to the growing economy. At the same time, he began a slow and calculated rise to power in the navy, starting as a member of a navigation council in 1661 and finally ascending to minister of the navy in 1669.²⁷ Colbert, who had a phenomenal capacity for work, applied the same rigor to the navy that he brought to the nation's finances, in order to protect maritime commerce and speed up colonization. His greatest challenge was rebuilding

the fleet, which from 57 ships in Richelieu's heyday (1630s) had diminished to a mere 26 ships by 1660. By contrast, Britain by then had 133 ships and the Netherlands, 101 ships. Colbert was faced with a massive task that the existing dockyards could not handle. He created new naval dockyards at Brest and Rochefort, and ordered ships from the Netherlands and Denmark as a stopgap measure. He also brought constructors from overseas to speed up the process (the greatest number, 37, came from the Netherlands).²⁸ However, Colbert was insistent that France develop its own shipbuilding capability, based on the best practices of other navies, and quickly established an espionage program that would be unrivaled in Europe for 70 years.

Colbert was particularly impressed by the economy with which the Dutch built their ships, and with the generally high quality of the British warships. He wanted his constructors to observe their techniques firsthand and report back to him. Accordingly, he sent a M. Laurents to the Deptford dockyard in Britain in 1663, then the Brest constructor Étienne Hubac to various dockyards in Britain and the Netherlands in 1669, followed in 1670 by Pierre Arnoul, then general commissioner of Toulon. They reported back on specific details of construction techniques and dimensions. In 1671 Colbert sent his 18-year-old son Jean-Baptiste, marquis of Seignelay, on an extended mission to Italy, England, and the Netherlands, in spite of his fragile health. Colbert, who was grooming Seignelay as his successor, gave him a very lengthy and detailed set of instructions on what to observe.²⁹

Although these voyages were arranged through official channels with the foreign governments, they were still espionage aimed at discovering and bringing back trade secrets held closely by other constructors. Seignelay's report on Dutch shipbuilding was filled with numerous perceptive observations on both advantages (e.g., the Dutch joined timber with wooden treenails, which swelled and tightened in water; the French used iron nails, which rusted) and defects (the Dutch did not allow their wood to season as did the French).³⁰ Seignelay also noted, as had Hubac and Arnoul before him, that the flatter bottoms of Dutch ships allowed them to draw less water—vital since their harbor entrances were shallow—and still retain a good measure of seaworthiness (see figure 2.2). The observations on British warships tended to concern hull proportions and masting, which Seignelay generally found superior.

Colbert ensured that his constructors received these “benchmarking” reports, but their response was naturally defensive; Brest constructors, for example, believed French hulls “split the water” better (i.e., were faster) than British ships, and in Toulon, the difference in masting was attributed to the better quality of wood available to the British.³¹ Colbert, however, was determined to change what he believed were



Figure 2.2

Comparison of Dutch and French midships. (After Seignelay, “Remarque sur la marine d’Hollande” [1672])

entrenched and outmoded ideas held by his constructors, and began issuing a series of regulations that would codify and standardize the “best practices” of both French and foreign dockyards. The first regulation, in 1670, was quite modest, dividing ships into five rates based on the number of guns. The second regulation, of 1671, insisted on more extensive changes based on the observations of Hubac and Arnoul in the Netherlands—for example, making the bottoms flatter so the ships would draw less water and not be damaged when grounding. It also created construction councils in Brest, Toulon, and Rochefort, which were composed of officers, intendants, and other administrators of the port, who met every two weeks to oversee the constructors and to observe whether the ordinances were being followed. This was one of the first steps in what would be a gradual process of more centralized oversight and control of design by administrators and not constructors.³²

Colbert continued to tinker with his regulations, aided by his son Seignelay, who took over more and more of the duties as minister of the navy.³³ The third regulation, in 1673, was highly detailed, fixing the proportions of length and beam, the methods for drawing the lines, and a host of other measures that left nothing to the discretion of the constructors.³⁴ It also specified that constructors were to build models of their proposed hulls in the form of a longboat (*chaloupe*), evidently capable of floating, which he would inspect before approving the ship for construction. This was the clearest indication yet of Colbert’s desire to wield more control over the design process, and of his mistrust that his constructors would carry out his wishes; his constructors certainly returned the lack of faith by continuing to build ships to their own ideas, even after the regulations were issued. This perhaps gave rise to Colbert’s concept that

a common set of design principles, based on scientific theory that they could not possibly dispute, was needed to guide his constructors.

Colbert believed that a “scientific” approach to ship design could make each ship of the French navy superior to those of its potential enemy by ensuring that it was optimally designed for fighting and required little or no refit. In modern military terms, Colbert’s idea was that scientific design would provide a “force multiplier” that would improve the fighting effectiveness of individual ships, helping redress France’s numerical imbalance with Britain and the Netherlands. This was certainly in keeping with his strategic efforts to promote scientific development in the related areas of navigation and artillery. On 10 September 1678, Colbert wrote a pivotal letter to the intendants of Toulon, Brest, and Rochefort, explaining his ideas:

Some time ago I resolved to have a project undertaken in all the ports, which is assuredly the most important and most necessary for the whole Navy. . . . My intention . . . is to work to establish a theory on the subject of the construction of vessels, that is to say, to establish the measures and proportions of the members and parts of each vessel so well . . . that it will be assured . . . of carrying sail well, that the batteries will be well-established, that it will fight well . . . in a word, that it will be perfect . . . and not require doubling nor trimming. . . .

I know this will not be an easy task. . . . You must choose the best vessels of each rate . . . and make plans and profiles of all the measurements . . . even each piece of wood, so that all the designs are correct down to the foot, inch and twelfth of an inch.

You will assemble a council of construction, which should be composed of only three or four persons at most, so that you make a proposal of a theory, and that you then take your knowledge and create a written estimate of all the measures and proportions necessary to make the construction perfect. I can easily tell you that the commission of constructors in England have formed this theory, upon which all the most beautiful and best English vessels are built, so you see it is not so difficult a thing as you first believed. Then explain to Mr. Duquesne these thoughts, on which he will shed much light.³⁵

Colbert and Seignelay followed this letter with repeated entreaties to their most senior admiral, Abraham Duquesne, demanding that he provide a treatise on his theory of construction.³⁶ Duquesne, by then 68 years old and the veteran of numerous battles that had won France control of the Mediterranean, was understandably slow in responding to this request, probably bewildered by the whole notion of a “theory” of construction and wondering why he was asked to take part in it.

Colbert and Seignelay were becoming exasperated, not only with Duquesne but also with their entire naval organization. They had been promised scale models of ships on numerous occasions, but never saw one.³⁷ None of their recommendations for adopting novel methods of construction from British and Dutch practice were being followed. None of their constructors were building ships exactly according to their

regulations—there was always some variation, albeit for defensible reasons. To them, the navy seemed incapable of change or of creating a new—or at least clearly understandable—theory of ship construction. But that was the least of their problems, for if they felt the navy was ignoring them, even worse was the fact that the king was ignoring the navy.

The Grand Canal at Versailles

Louis XIV, despite his endless declarations of land wars and fondness for accompanying his generals in the field, showed little interest in the workings of the navy.³⁸ He never once reviewed the French fleet (even though Charles II of Britain did so, at the outbreak of the 1672 war with the Netherlands), and almost never visited any of the ports. Colbert worked incessantly to find ways of attracting the king's attention in order to obtain more funding. Louis was far more interested in the arts (he danced in professional ballet performances), and he always enjoyed a good spectacle. Colbert, aware of this, tried this tack on several occasions to gain the king's interest; when the resident elephant at Versailles died in 1681, Colbert arranged to have the Academy of Sciences dissect it in front of Louis and his court.³⁹

One of Colbert's ideas for a comparable naval spectacle was based on an event a century before (July 1574), when the Venice Arsenal built a galley in a single day, before the eyes of Henry III of France. Colbert prepared his various dockyards to be ready for such an event should the king ever visit, and had them do several trial runs, including having a galley built in November 1678 at Marseille in two days, and a 40-gun frigate built at Toulon, in July 1679, in just over seven hours. The construction techniques used would not be out of place in a modern dockyard, including the use of prefabricated planks and frames, and the division of the workforce into teams wearing colored caps for easy identification.⁴⁰ However, the king saw none of this, for the few times he visited dockyards were specifically to view ships' sculptures. This all made Colbert's reluctant decision to fund the construction of Versailles seem prescient.

Louis XIV had created the glorious château at Versailles to outdo that of his deposed superintendent of finances, Nicolas Fouquet, whom Colbert had replaced in 1661. It was a colossal work; over a million tonnes of soil and rock had to be shifted to fill in the marshy terrain and create the gardens, and the entire village of Trianon was razed to build a château for guests. Colbert deplored the enormous expense, seeing it as the folly of a youthful and capricious king, but the idea of creating a large canal within the gardens brought about his tacit, if not formal, approval; Colbert was quite interested in hydraulic projects, and saw this as a way of gaining a better understanding of the subject.⁴¹

The Grand Canal, named after the principal Venetian waterway, was dug out from a small creek starting in 1668. Built in stages, it was eventually in the shape of a cross, with a main waterway 1,800 meters long and 62 meters wide; the transverse arms spanned 1,500 meters. While it was still under construction, the first small boats appeared on it, nine of various types, richly decorated, to entertain the king on his evening promenades. In 1671, the ambassador of Venice offered Louis two gondolas and four gondoliers; and in 1675, England delivered two yachts. More boats of various descriptions came from across France, Naples, and the Netherlands; at its apogee, the Grand Canal fleet comprised an astonishing 60 vessels.⁴² To build and maintain the fleet—which was an official part of the navy—a nautical “corporation” was established and housed at Versailles, comprising naval constructors, sailors, carpenters, caulkers, sculptors, and their families.⁴³ For Louis XIV, this was his pleasure fleet. For Colbert, however, the Grand Canal fleet became the means of bringing the navy to Louis XIV.

Apart from getting the king interested in the navy, Colbert (or his son Seignelay; it is not clear which one) gradually developed the idea of using the canal as a sort of testing tank, not in the modern sense of a facility to tow models under fixed conditions (crude towing tanks were in fact being used at the time in Britain; see chapter 3), but of a place where scale models of ships could be compared and their performances evaluated. It was at the Grand Canal that Colbert’s idea of a theory of construction of ships, and his desire to interest the king in the navy, converged.

Bernard Renau d’Elizagaray, the *Dérive*, and the “Ellipse Theory” of Ship Construction

The secret Treaty of Dover in 1672 had marked the beginning of a short-lived alliance between Britain and France. Louis XIV took advantage of this truce to order two yachts from the renowned British constructor Anthony Deane, which were delivered to Versailles in late August 1675. While Deane was at Versailles to oversee the delivery, Louis XIV asked him a child’s question: “Why can a vessel sail against the wind?” Deane was perhaps unable to respond adequately, for he posed the question to a 23-year-old member of Colbert’s household who, despite his youth, was already making a name for himself as an expert in naval matters—Bernard Renau d’Elizagaray.⁴⁴ Renau, as he called himself, was tiny even as a child (his nickname was “Petit Renau”), which made many people feel protective of him. He had been adopted when he was 13 years old into the household of Charles Colbert de Terron, intendant of the Rochefort dockyard and cousin of Jean-Baptiste Colbert—in a sense, he was Colbert’s second cousin. Renau was a very bright boy, and under Colbert de Terron’s guidance, he became well read

in mathematics, navigation, and philosophy, especially the works of René Descartes, Nicolas Malebranche, and Ignace Pardies. He attended the biweekly construction council meetings at Rochefort, and even took over some of Colbert de Terron's duties as intendant during his long absences.

So when Deane repeated Louis XIV's question to him, Renau confidently told Hubert de Champy, baron of Desclouzeaux (at the time, the commissar general of naval installations) that he could not only demonstrate why vessels sailed upwind, he could even determine their position.⁴⁵ Renau's confidence came from knowing of an analysis of the problem published two years earlier by Ignace Pardies. Pardies, a Jesuit priest and mathematician, had planned to write a series of books on physics, but completed only one; *La Statique; ou la Science des forces mouvantes* (Statics; or the Science of Moving Forces) was published in 1673, just weeks before his death.⁴⁶ Pardies intended it to be a work both of original theory and of instruction, and gave numerous practical examples to illustrate his theorems.

To demonstrate the vector composition forces on an object in a resisting medium, Pardies took the example of a ship under sail (figure 2.3). This concept, described further in chapter 3, had been demonstrated geometrically in 1636 by the French mathematician Gilles Personne de Roberval.⁴⁷ In figure 2.3, line $a-l$ is the sideways component of force of the wind on the sail; $a-h$, the forward component; and $a-f$, the resultant. Pardies explained that if the body were ball-shaped and had equal resistance in all directions, it would sail along the line of the resultant force $a-f$. However, a ship's shape has greater resistance sideways than it does forward, so its *dérive* (line $a-i$) could be determined by the ratio of sideways to forward resistance, which Pardies guessed was about 100 times greater.⁴⁸

Notably absent from this analysis was any mention of "speed" or "velocity" in the discussion of force; at the time, there was little consensus on the relationship between the two. However, the implication of this analysis was that fluid resistance was a direct function of velocity. It would appear that Pardies either did not know or did not believe that fluid resistance was a function of the *square* of velocity, so the simple geometrical relationship he described would not hold.⁴⁹

Pardies's analysis of the *dérive* is undoubtedly what Renau had in mind when he promised an answer to Desclouzeaux, although he waited four years to deliver on it. In 1679 (at the age of 27) Renau was invited to Versailles to teach the principles of mathematics and navigation to the king's illegitimate son Louis de Bourbon, count of Vermandois, who was being raised by Colbert and at age 12 was already the admiral of the fleet. It was at this time that Renau wrote his first memoir on ship design and

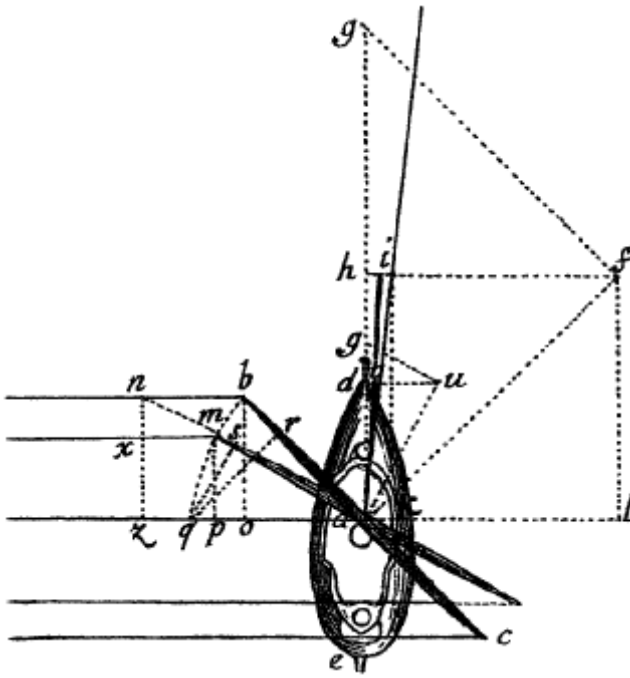


Figure 2.3

Pardies's explanation of forces on a ship. (Pardies, *La Statique; ou la Science des forces mouvantes* [1673], p. 239). Credit: Archives and Special Collections, Dickinson College, Carlisle, PA.

construction, titled “Mémoire sur les constructions des vaisseaux, dans lequel il y a une méthode pour en conduire les façons” (Memoir on the Construction of Vessels, in Which There Is a Method for Creating the Narrowing Lines). The 17-page handwritten document, with marginal notes and drawings, was never published.⁵⁰ It may have been an educational text for the young admiral, although it is not clear whether Renau wrote it while still at Rochefort or upon coming to Versailles. In the memoir, Renau went beyond the king's original question to explain not just how to estimate the sailing direction of a ship, but also to provide a theory for developing the hull lines based on this explanation. It is possible that Renau was inspired to write this “Mémoire” by Colbert himself, who by this time was frustrated by the navy in his search for a “theory of construction.”

The “Mémoire” is noteworthy for being the first identified attempt to provide a theoretical basis with which to evaluate a ship design—in effect, the first known work of naval architecture. The distinction from manuscripts and books of ship construction,

such as Charles Dassié's 1677 *L'Architecture navale* (Naval Architecture),⁵¹ contemporaneous with Renau's manuscript, was that such works gave predetermined rules for hull proportions and forms based on the practice of constructors. While these were far more useful in actual shipbuilding at the time, Renau's manuscript marks the initial step toward creating not a set of predetermined design rules but a body of theory based on physical laws that would enable constructors to determine the characteristics and performance of a ship before it was built.

Although Renau never mentioned Pardies by name, he was heavily influenced by his analysis. The "Mémoire" began in a manner similar to that of *La Statique*, with an explanation of the movement of a spherical ball in a medium to introduce the concept of resistance. Renau then analyzed the *dérive* of a ship, taking (as did Pardies) the sideways resistance to be 100 times greater than the forward resistance (figure 2.4). Like Pardies, Renau never mentioned "speed" or "velocity" in his analysis, with the resulting (but unstated) assumption that resistance was proportional to speed.

Renau then entered into the heart of the matter—determining the best hull lines of a ship so as to give the least *dérive*, that is, ones which offered the least forward resistance compared with the sideways resistance.⁵² Renau was particularly careful not to suggest changing the proportions of ships, arguing that the problems of, say, reducing the beam would outweigh the advantages. In fact, Renau was well aware that the proportions of length, beam, and other components had already been fixed by Colbert's 1673 regulation, and astutely decided not to go up against his supporter's decisions. Rather, Renau proposed to show, within those proportions, which lines would be best. For him, those lines would be ellipses.

Renau's arguments leading up to this conclusion are difficult to follow, internally inconsistent, and in fact completely wrong even by the mathematics of his day. His line of reasoning went something like this (see figure 2.5): The rectangle ADBC is 10 times longer than wide, so its resistance to forward motion is 10 times less than its resistance to sideways motion. In other words, Renau was implying that the *dérive* for the rectangle is proportional to the surface areas, in this case $Area_{fwd}/Area_{side} = 1/10$. The inscribed triangle ABC, he argued, has two components of resistance to *dérive*: the component proportional to the surface areas (the same as the rectangle), plus a second component due to the obliquity of the side AB, equal to the sine of angle α , which he takes as 1/10 (in fact, it is 0.0995).

Thus, the *dérive* of the triangle, Renau claimed, is $1/10 \times 1/10 = 1/100$, or 10 times less than for the rectangle. Although the triangle, Renau went on to state, would offer the least *dérive*, it would tend to veer too much during maneuvers. In addition, for

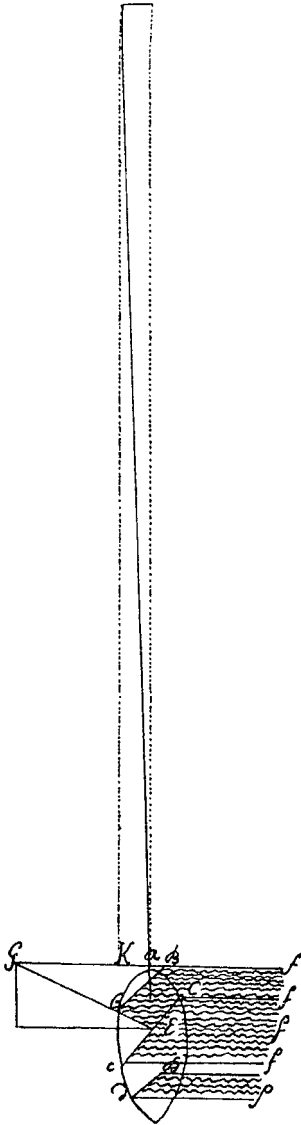
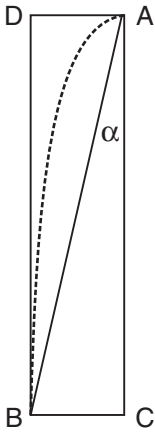


Figure 2.4

Dérive of a ship according to Renau. (Renau d'Elizagaray, "Mémoire sur les constructions des vaisseaux" [1679], p. 4). Credit: Centre Historique des Archives Nationales, Paris.

**Figure 2.5**

Analysis of Renau's argument that ellipses offer the least *dérive*.

practical reasons (probably meaning for actual construction in wood), the lines of the ship must be parallel to its axis at the middle (point B), and perpendicular to the axis at the ends (point A). The only geometrical curve that can meet these requirements, according to Renau, is the ellipse (here A–B in dashed lines), which is therefore the ideal shape for hull lines.⁵³

It should be noted here that Renau's arguments were founded in the most current mathematical ideas of his day. He obtained from Descartes's *Discours*⁵⁴ the idea of the "geometrical curve" (i.e., one that could be described as an algebraic equation), as opposed to a "mechanical curve," such as those of multiple circular sweeps then used by constructors. And, as stated, he borrowed heavily from Pardies, whose work had been published only six years prior. But he made fundamental errors of analysis right from the start, and continued to make such errors throughout his career, clearly demonstrating his lack of formal, rigorous training in mathematics. In this example, using Pardies's assumption that resistance was proportional to surface area, a careful analysis of resistance to *dérive* would have made use of Roberval's vector composition of forces, applied perpendicularly to each surface, and would have demonstrated that the *dérive* for both the rectangle and the triangle would have been identical. Such mathematical examinations of forces were routinely done by more rigorously trained contemporaries such as Christiaan Huygens and John Wallis.

Renau, having established the ellipse as the preferred shape, went on to explain how to use the "machine" (called an ellipsograph or elliptical trammel) to construct the curve. A series of reference points had to be established for each curve, using a long

set of algebraic equations, on which to set the frame of the machine; the curve would then be traced in pencil or chalk. The concept of the ellipsograph was certainly not new—it had been in use since 1600⁵⁵—but Renau was proposing it at a time when ship plans (i.e., line drawings) at a reduced scale were still rarely drawn in France. As discussed in chapter 1, most French naval constructors in 1679 were working at full scale, drawing the figures of the frames directly on the floor of the molding loft; for that reason, circular curves were preferred because they could easily be laid off, using a chalk swung at the end of a string. A full-scale ellipsograph, 25–30 meters long, would have been impossible to manipulate. Thus, its practical usage would have been limited to making a reduced-scale drawing on paper, with the lines then scaled up and transferred to a full-scale mold in order to construct the frames.⁵⁶

Whether Colbert inspired Renau to develop his “Mémoire” and ellipse theory, or whether Renau brought them to him unbidden, it must have seemed to Colbert a godsend; here was the scientifically based, rational theory for ship construction that he had been waiting for. It was now a question of testing the concept, so Colbert and Seignelay decided to send Renau back to Rochefort in April 1680 to try out his new machine.

It is not hard to imagine that constructors would view this process with skepticism. Renau’s ellipses were the esoteric “geometrical curves” from Descartes, not the practical “mechanical curves” that could actually be drawn. However, the problem was not the use of ellipses, but the mathematical knowledge required to work out the equations for them. The French constructors, like other constructors of that era, were highly trained professionals who knew the practical uses of arithmetic and geometry for their craft, but often had little formal education, in many cases to the point where they could neither read nor write. The mathematical basis for the theory that a hull must be formed by ellipses in order to have a minimum *dérive* would have equally escaped them.

The Grand Canal and the 1681 Construction Conferences

Colbert and Seignelay had sent Renau to Rochefort to meet and work with Anne Hilarion de Cotentin, count of Tourville, then a young (38) but an experienced naval captain. Colbert and Seignelay found in Tourville an openness to new ideas that was lacking in Abraham Duquesne, then almost 70. Tourville was in Rochefort in 1680 with his favorite constructor, an Italian named Biaggio (Blaise) Pangalo⁵⁷ when he received orders from Seignelay to examine Renau’s theory of ship construction.

The evidence from the correspondence of the period February–September 1680 suggests that Colbert’s (or Seignelay’s) plan was the following⁵⁸:

1. Seignelay would exhort both Tourville and Duquesne, apparently without telling the other, to develop competing theories of construction, which would be tested using ship models at Versailles.⁵⁹
2. Under Tourville's oversight, Renau would create a ship's drawing based on the design provided by Pangalo. He would demonstrate to Honoré Mallet (the principal constructor at Rochefort) and his subordinates the theory and use of the ellipsograph, even though Mallet could neither read nor write. Pangalo and the Rochefort constructors would then build a model of the "ellipse" ship.⁶⁰
3. A parallel effort was already under way under Duquesne's oversight in Toulon, where a ship model with conventional lines was being built by two father-son teams of constructors, François and Nicolas Chapelle and Laurent and François Coulomb.⁶¹
4. In the final step, the two models—Renau's ellipse ship and Duquesne's conventional ship—would be brought to the Grand Canal at Versailles. In addition to piquing the king's interest in the navy, the models would be tested side by side during a series of construction conferences, to take place in the winter of 1681. The "winner" would be used to establish once and for all the methods and dimensions for building ships.⁶²

It was evidently quite difficult for the Rochefort constructors to use Renau's ellipsograph, or to understand why they should bother. Tourville noted that there was little real difference in the choice of lines, but that Pangalo's methods were much easier to understand. Nevertheless, Tourville wrote several letters to Colbert expressing confidence that the machine, though difficult to use, would eventually create the desired hull lines. By late August 1680 the lessons on Renau's machine were completed, to no one's great satisfaction, but showed that his theory did work in principle. Renau was ordered to go to Brest to instruct Étienne Hubac (son of the principal constructor) on the use of the machine before returning to Versailles in October.⁶³

Renau's ellipse model (later called *Modèle*) was 10 meters long, displaced about 17 tonnes and was normally sailed by six men. It was completed in late August 1680, then dismantled and sent by boat to Le Havre and down the Seine to Saint-Cloud, to be transported overland to Versailles in late October; however, its reassembly was delayed until June 1681. Duquesne's conventional model, called *Frégate*, was much smaller at 5 meters long, about 2 tonnes in weight, and could fit only one or two men on deck. It was begun around January 1680 but not finished until the end of the year. On 15 January 1681, Duquesne and the young Nicolas Chapelle left Toulon, the model

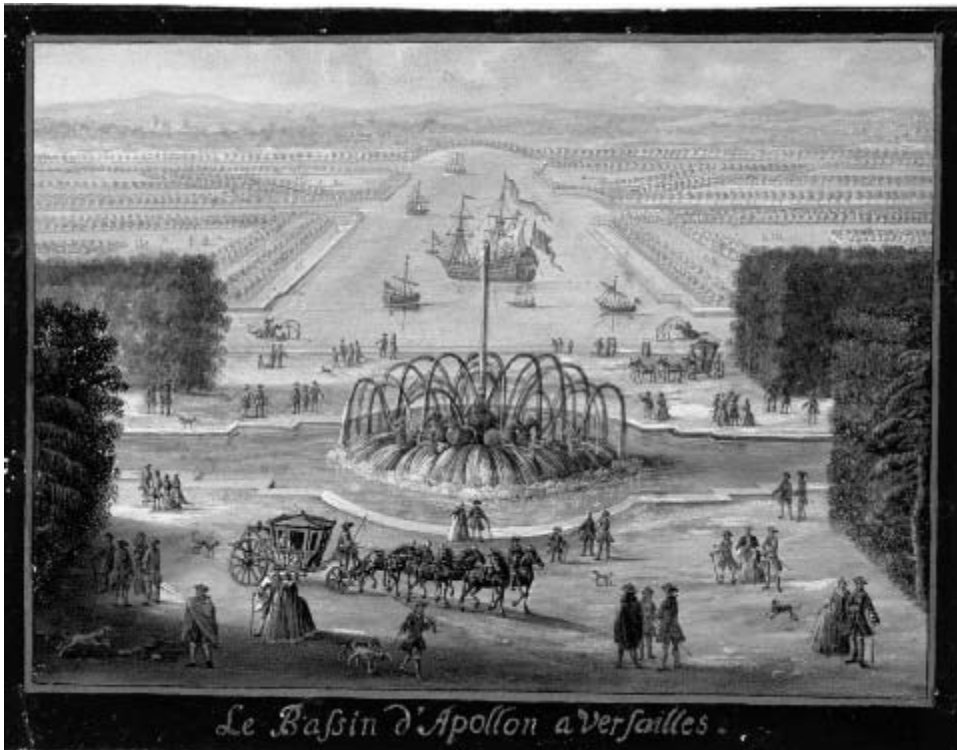


Figure 2.6

Grand Canal fleet at Versailles, with *Modèle* in foreground and *Frégate* behind. Gouache of the Bassin d'Apollon at Versailles (1705), Châteaux de Versailles et de Trianon. Credit: Réunion des Musées Nationaux/Art Resources, New York.

filled with Muscat wine as a present to Colbert; it probably arrived at Versailles in mid-February.

Figure 2.6 shows the Grand Canal fleet, with *Modèle* dominating the foreground and *Frégate* immediately behind it. As the painting shows, the size difference between the two was enormous; although both models were ostensibly of a fully rigged 60-gun ship, *Modèle* was almost 10 times bigger by displacement than *Frégate*. It was painfully apparent that Colbert's and Seignelay's extensive preparations to test a new theory of ship construction by having two models compared side by side were completely in vain. Not being to the same scale, no relevant comparisons could be made.⁶⁴ Although these models probably went some way to piquing the interest of Louis XIV in his navy,

as Colbert and Seignelay intended, they apparently soured the two ministers on any further model tests.⁶⁵ Tourville, however, made two other unenthusiastic attempts at comparing ship theories using models: the first, in 1681 at Brest, was a repeat of the Versailles experience; and the second, in 1686 at Toulon, with the Jesuit mathematician Paul Hoste, whose ship theories involved semicircular bows and sterns.⁶⁶ These experiences effectively marked both the beginning and the end of model testing in France for almost a century.

Colbert and Seignelay had intended for the Versailles model tests to be made during the long-awaited construction conferences, and they must have been bitterly disappointed; nonetheless, those conferences still took place. Yet for all the importance that they evidently placed on their outcome, no direct records of the conferences survive. It is not known for certain when and where they occurred, nor who the participants were. The agenda is not known, nor are the decisions taken. The following account must therefore be considered informed speculation gleaned from only a few primary sources and many conflicting secondary sources.⁶⁷

The conferences took place at the royal château at Saint-Germain-en-Laye, where Seignelay had his offices. They began on or about 23 February 1681, soon after Duquesne had arrived with *Frégate* and the shock of futility had worn off, and lasted about two months. The meetings were presided over by Admiral of the Fleet Louis de Vermandois, though given that he was only 14 at the time, Seignelay guided him on a day-to-day basis. However, Seignelay was consumed with preparations for the looming war with Alger (today the city of Algiers), since tensions had risen with Dey Baba Hassan I. Admiral Duquesne and Captain Tourville were the senior navy officers present. Biaggio Pangalo and Renau were with Tourville, representing Rochefort; Nicolas Chapelle, though young, was with Duquesne, representing Toulon (Laurent Coulomb may have arrived later); Étienne Hubac, also young, came in late March, at the request of Colbert, to represent Brest.

The meetings probably took place several times a week. The principal discussions involved the correct proportions for each rate, resulting in a series of dimensions that were fixed by the group, to be approved by Colbert. The theory and practice of Renau's ellipsograph was discussed, although the fact that his pupil Louis de Vermandois was presiding ensured its acceptance.⁶⁸ Colbert periodically came from Versailles, in order to take the important decisions. The king came by once or twice.

In March, Louis XIV's chief military engineer and expert on siege warfare, Sébastien Le Prestre, lord (later marshal) of Vauban, attended the conferences to assist with the plans against Alger, during his separate visit with Minister of War Louvois.⁶⁹ It was in

this period that the young Renau, possibly with the help of Vauban, proposed the novel concept of putting mortars, used in land attacks to lob shells over city walls, on specially built ships (called *galiotes à bombes*, mortar ships or bomb ketches), in order to attack fortified cities such as Alger.⁷⁰ The idea was accepted; in late 1681 Colbert ordered five of the ships to be built under Renau's direction, with another dozen ships built soon thereafter to participate in campaigns against Alger, Genoa, Tunis, and Tripoli. Renau's mortar ship soon became a standard fighting vessel in the French navy, and was later adopted by many other navies.⁷¹

The conferences ended on or around 9 April 1681, when Duquesne left to take over his fleet in Toulon; a week later Pangalo and Hubac went to Brest to begin work on a new ship based on Renau's lines. Renau submitted his ellipsograph for approbation by the Academy of Sciences; on 3 May the architect Nicolas-François Blondel and the mathematician Edmé Mariotte reported their satisfaction and approval.⁷² Renau went back to Brest in June to work with Hubac on another model of an ellipse ship, then to Le Havre in August to work with the constructors Étienne Salicon and Jacques Doley on the 58-gun *Arrogant*, apparently the first ship to be built to his ellipse theory. He then turned his attention to the mortar ships, and left for Dunkirk in January 1682 to work with the constructor H. Hendrick on *Bombarde*, the first of these ships, though it is not clear if they had elliptical hull lines. By June of that year, Renau was on his mortar ships fighting Alger, which marked the start of a seven-year military campaign on land and sea that effectively halted his activities in ship construction until 1690.

What was the outcome of the conferences? Pierre Bouguer, writing about them some 65 years later in *Traité du navire*, claimed:

It appears that if Naval Architecture was perfected, it was in the conferences that took place in Paris towards 1681 or thereabouts. . . . The conferences resulted in a considerable advantage for the navy. They fixed the principal dimensions of ships, the same proportions as one always sees today, those which are found in different books and which were authorized by Ordinance of the dockyards in 1689. But what was infinitely preferable, M. Renau communicated a controlled method to form the plans and profiles of ships, in adjusting almost all parts against each other, to make their form more uniform and symmetric; instead of the practices they had followed until then, always abandoning the disposition of each work to chance or to the caprice of the worker.⁷³

The conferences certainly loomed large in Bouguer's mind. Based on his testimony, historians starting with John Fincham in his 1851 *A History of Naval Architecture*,⁷⁴ and continuing right through the twentieth century, attributed the beginnings of theoretical naval architecture to these conferences. Were they in fact a beginning for naval architecture—that is, did they satisfy Colbert's original desire for a "theory of con-

struction"? And did they result in any significant changes that would have given the French navy a "considerable advantage," as Bouguer claimed?

Colbert's idea for a "theory of construction" was really quite pragmatic: a set of rigid rules for constructing each rate, so that, say, a 60-gun ship built in Toulon would be exactly the same as one built in Brest. His desire for a scientific basis for those rules, as laid down by Renau, was simply a means to end; after all, in his mind no one could argue with such a rational basis for design, as his constructors did endlessly over his suggestions to incorporate Dutch or British practices. Bouguer stated that the conferences fixed the dimensions of the ships, which were enshrined in the ordinance of 15 April 1689. This was a massive document—an ordinance was really a series of regulations—covering all affairs of the navy, comprising 405 pages and divided into 23 books. Only book 13 (Ship Construction), title 2, less than a page long, concerned dimensions and proportions. The entire set of rules for building ships, based on the months of deliberations of the construction conferences, amounted to seven lines: for each rate, only the length, beam, and depth were fixed.⁷⁵ Colbert's original intent was, as stated, to describe "each piece of wood . . . down to the foot, inch and twelfth of an inch." The 1689 ordinance was a far cry from that. True, in the eight years that had passed since the conferences, Colbert had died (in September 1683) and his son had taken over; it is possible that Seignelay had allowed the original directives to be watered down, due to pressure from his constructors, but for whatever reason, Colbert's original vision did not come to pass.

Did the decisions taken during the conferences actually improve the French navy, as Bouguer claimed? The dimensions prescribed by the 1689 ordinance were in fact identical to those of the ships considered the best in the fleet, such as *Royal Louis* (104 guns) and *Saint Esprit* (70 guns), many of which were built before 1671.⁷⁶ The ordinance not only had no basis in Colbert's "theory," it did not even represent a significant step forward in thinking. Moreover, although the 1689 ordinance was theoretically in force until 1765, constructors never followed it. For example, first-rate ships were specified to be 163 *pieds* long and 44 *pieds* beam. An examination of "standard" 90-gun ships (first-raters), 17 of which were built from 1689 to 1693, shows a variation in length from 151 to 170 *pieds*, and beam from 42 to 46 *pieds*.⁷⁷ Bouguer also claimed that the teaching of Renau's method conferred an advantage to the navy. Colbert had directed his constructors to use Renau's ellipsograph to create the hull lines, but in the 1689 ordinance there was no trace of this requirement. A minor ordinance had been issued on 16 September 1683, a few days after Colbert's death, requiring constructors to submit plans of ships to the construction council, but did not specify how the hull lines were to be drawn, nor did it require the lines to be

ellipsoids.⁷⁸ However, as with ship dimensions, even this regulation was honored more in the breach than in the observance. In February 1684 Renau wrote to Seignelay, explaining that in order to perfect the French navy and use construction timber more efficiently, all ships should be built to his elliptical method; moreover, he should design all the ships himself, oversee the keel-laying and placement of frames of each ship, and receive reports on the performance of each.⁷⁹ Renau was of course never granted that overarching authority. Although a dozen or so of his “ellipse ships” were eventually built (and gave generally good service), almost all were those supervised by Renau himself, and the technique did not spread to other constructors.⁸⁰

What of Colbert’s attempts to “herd cats”? To recap: he had benchmarked the competition by sending spies to Britain and Holland; he had developed “best practices” through a series of regulations, culminating in the 1681 construction conferences; at those conferences, he got his senior management—Tourville and Duquesne—on board with the changes, and he ensured follow-through by codifying the results of the conferences (published in the 1689 ordinance) and by sending Renau to various ports to oversee the design of ellipse ships. Yet the constructors in the various ports did not even pretend to follow these orders, even though they came from the most powerful man in France. Part of the reason must have been Colbert’s death only two years after the conferences; though Seignelay was a brilliant and hardworking official, he did not wield power in the same uncompromising way as his father. More relevant to the situation was the fact that each dockyard was its own world, where the education and training of its constructors (often fathers and sons) generally took place within its walls, despite the occasional arrival of a constructor from another dockyard, or from abroad, on the orders of Colbert or Tourville. As stated in chapter 1, these constructors were highly professional men who knew their business and built good ships, not blindly to old ideas but based on sound practice that they themselves improved through experience. They did not see any advantages to the construction techniques of their erstwhile enemies Britain and Holland, and they were even somewhat suspicious of other French dockyards.⁸¹ And by no means did it make sense to suddenly change their tried-and-tested practice in favor of a theory they could neither read nor understand, espoused by a twenty-something nepotist who had never built a ship in his life. They could, and did, wait out Colbert and his successors—for over 80 years, as it turned out. It was only after the French navy set up the School of Engineer-Constructors of the Navy (1765), where all constructors began their shared education and training in those new methods before being sent to the dockyards, that a common set of design principles could be developed and applied across the entire fleet.

The Debate over the *Dérive*

In 1683, Renau's two primary naval patrons died—Colbert and 16-year-old Louis de Vermandois—so he took leave of the navy and became an army officer, accompanying his new mentor, Vauban, to shore up France's northern fortifications and to lay siege to cities in Flanders and Luxembourg, while learning firsthand the art of the military engineer from the greatest of them all. From that time until 1688, with the exception of a naval campaign against Genoa in 1684 and a brief stint with Pangalo at Toulon in 1685/1686, he was almost continuously engaged in land warfare, mostly building fortresses and citadels with Vauban. It was probably during this time that he took up his unpublished "*Mémoire sur les constructions des vaisseaux*" and revised it into a much different work, completely removing his ellipse theories of construction and focusing on the *dérive*, which he had treated perfunctorily in his "*Mémoire*." He eventually titled the book *De la Théorie de la manoeuvre des vaisseaux* (On the Theory of the Maneuvering of Vessels).⁸²

Renau later claimed that he had almost completed the first draft of the book (probably around 1685) when he became aware that the underlying theory was false, and so he had to redraft the entire work based on these new principles.⁸³ The probable catalyst for this revision was the newly published *Traité du mouvement des eaux* (1686) by Edmé Mariotte, which popularized the notion that fluid resistance against an inclined plane was a function not of v (velocity) and $\sin \alpha$ (angle of attack), but rather of v^2 and $\sin^2 \alpha$ (which will be discussed further in chapter 3). Renau had originally based his *dérive* on Pardies's unstated assumption that resistance was directly proportional to speed; that was now invalid, and it was time for a rewrite. This result may also have called into question his ellipse theories, perhaps explaining why he removed it. His redraft probably took place around 1686–1687.

Renau offered the manuscript to Seignelay in 1687, claiming that it was "more useful for service than there has ever been until now."⁸⁴ The text was edited by Joseph Sauveur, a military engineer who, like Renau, trained under Vauban and may have worked with Renau on the battlefield. Sauveur, later known for his work on acoustics, had assisted Mariotte during the experiments that led to the v^2 resistance laws, and may have inspired Renau to rethink the *dérive*. Vauban probably knew about the imminent publication, as in 1688 he told Minister of War Louvois that although Louvois had never heard of Renau because he was in the navy, Renau would "become better known . . . than all the others in M. Seignelay's department put together."⁸⁵ Yet for unknown reasons, Renau's name did not appear on the book when it was published

in 1689; Sauveur was listed as the editor, and Renau remained the anonymous author for many years.⁸⁶ The publication of this work may have contributed to Seignelay's naming of Renau the first inspector general of the navy the following year.

Renau's *De la Théorie de la manoeuvre des vaisseaux*

De la Théorie de la manoeuvre des vaisseaux (figure 2.7) was devoted entirely to the question of maneuver, as the title implies. It was laid out more systematically than Renau's previous "Mémoire," beginning with an analysis of the forces on sails, hull, and rudders, followed by a geometrical derivation of the *dérive*. It then addressed the issues of maneuvering under different wind conditions, followed by an analysis of the maximum angle that the rudder should make with the keel for greatest turning effort. The book finished with several nomograms to geometrically determine the best position of sails, depending on the wind. In no manner was the book the "theory of construction" desired by the late Jean-Baptiste Colbert, for it provided no guidance on the design or building of a ship. Yet to the extent that it presented several means of predicting the performance of a ship using geometrical analysis, *De la Théorie de la manoeuvre des vaisseaux* can be considered the first published work of naval architecture.

Renau began by stating several times the laws Mariotte worked out: that the force of water or air was directly related to v^2 and $\sin^2\alpha$. The *dérive* would be a function of the relationship between the sideways and forward resistances of the ship, based on the square laws. For example, if the sideways resistance were 100 times greater than the forward resistance (as he had assumed in his "Mémoire," based on Pardies), then the sideways speed would be 10 times less than the forward speed. Renau admitted that "it would be very difficult to determine this Relation from the knowledge of the figure, and Proportions of the Ship, [so] here is a Method whereby it may be known."⁸⁷

Renau's method of estimating the *dérive* illustrates the very rough state of naval architecture at the time. Figure 2.8 shows a ship on heading M–K, with the wind at A; the actual course is found by sighting along two points on the coast (the rock at L and the cape at H) which do not change as the ship advances; and the *dérive* is the angle between the two. Once the angle of the *dérive* was known for a particular speed, the ratio of resistances could be determined.

Up to this point, Renau's arguments were generally correct mathematically, although neither he nor his contemporaries could have understood that the lateral resistance of a sailing ship (nowadays called the side force) is actually a hydrodynamic result of the sideways lift and drag of the hull; that knowledge was not fully



Figure 2.7

Frontispiece to *De la Théorie de la manoeuvre des vaisseaux*. Credit: John Carter Brown Library, Brown University.

developed until the twentieth century.⁸⁸ But Renau went on to provide a diagram that again demonstrated his lack of formal mathematical training, which apparently did not go far beyond basic geometry, and proved to be the source of the first great controversy in naval architecture. Figure 2.9 shows his diagram of how to calculate both the speed of the ship at any heading and the *dérive*, assuming a fixed angle between wind and sail; below it is an explanatory illustration.

Renau constructed a semicircle of ship speeds at different headings with respect to the sail (semicircle 1). He used the law that any triangle constructed within a semicircle, using the diameter as a base, must be a right triangle, in order to set up the equation to derive the ship speed BK at any heading, as a function of the maximum speed BG⁸⁹:

$$BG^2 = BK^2 + KG^2 \text{ so}$$

$$BK^2 = BG^2 - KG^2, \text{ i.e., } BK = \sqrt{BG^2 - KG^2}.$$

The problem with his use of geometry was that Renau knew that resistance was proportional to v^2 , so he *thought* that he accounted for it by using the squares of the sides of the right triangle to derive the hypotenuse (i.e., speed). In fact, if the same problem is expressed in trigonometric terms (where β = the angle of the ship to the sail), the flaw in the argument becomes clear:

Geometry

$$BG = v_{\max}$$

$$BK = v_1 = v_{\max} \sin \beta$$

$$KG = v_x = v_{\max} \cos \beta$$

Resistance

$$R = v^2$$

$$R_{\max} = v_{\max}^2$$

$$R_1 = (v_{\max} \sin \beta)^2$$

$$R_x = (v_{\max} \cos \beta)^2$$

$$v_{\max}^2 = (v_{\max} \sin \beta)^2 + (v_{\max} \cos \beta)^2 = v_{\max}^2 (\sin^2 \beta + \cos^2 \beta)$$

$$\text{but } \sin^2 \beta + \cos^2 \beta = 1$$

$$v_{\max}^2 = v_{\max}^2 \text{ so } v_{\max} = v_{\max}.$$

In other words, the trigonometric equations reduced to an absurd result; Renau had not accounted for the fact that resistance is the square of velocity.

Renau accounted for the *dérive* using semicircle 2, in which the ship speed BL is reduced from BK by the ratio of forward speed to lateral speed (BI/BG). Once again,

the same flaws as in the first argument apply: the *dérive* as calculated by Renau did not account for resistance as the square of the velocity. In addition, Renau implicitly assumed that the *dérive* was the same for all headings, a notion that would later be contested by the mathematician Johann Bernoulli.

Renau used these (erroneous) results to develop several complicated nomograms that would allow a pilot to derive the speed of a ship at different headings, sail angles, and values for *dérive*. He then provided a brief geometrical demonstration of the situation of the rudder, showing that it reaches its maximum effectiveness at an angle of about 55°.

The Beginnings of the Debate over the *Dérive*

The errors above were not noted at first; this was the first book of its kind to predict maneuvering and sailing performance in a mathematical way (instead of simply providing how-to-build rules), and it undoubtedly took some time for the ideas to percolate in learned circles. It received favorable reviews in 1689 in *Journal des sçavans* and in 1690 in *Acta Eruditorum*.⁹⁰ The British naval administrator Samuel Pepys admired it, though more as an example of the “backwardness of England (in comparison with France) in all things relating to the improvement of the science and practice of Navigation,” since no British person had ever written anything like it.⁹¹

In 1692, the Jesuit mathematician Paul Hoste published a treatise on maneuvering as part of his textbook on mathematics.⁹² He also complimented the “author of the theory of maneuvering” (Renau was still anonymous), and gave credit to his “ingenious and solid manner” of treating four or five of the most difficult problems.⁹³ Hoste argued, however, that it did not go far enough for a “perfect” understanding of the maneuvering of vessels, especially under tactical conditions. In fact, Hoste’s work was much more tactically oriented than Renau’s, for tactics was an abiding interest of his; he had written a treatise on the subject the year before, based on Tourville’s memoirs, which would ultimately be published in 1697 as *Art des armées navales* (The Art of Naval Armies), the first major work on tactics at sea.⁹⁴ Hoste also proved himself to be a superior mathematician, using trigonometry instead of basic geometry to derive the speeds of ships as a function of the angle of sails and the most advantageous rudder angles, although his results were not much different from Renau’s. Yet Hoste’s little treatise went virtually unnoticed; it was scarcely mentioned in other literature of the day, and Hoste himself did not reprise it in his 1697 *Théorie de la construction des vaisseaux*.

The First Period of the Debate over the *Dérive* (1691–1696)

Unlike Hoste's treatise, Renau's book was noticed, particularly by Christiaan Huygens, who in 1693 was living in The Hague when he was given the book to review and critique by Jean Le Clerc, the editor of the Amsterdam review *Bibliothèque universelle et historique*. The book did not catch Huygens unaware of the problems of maneuver; he had scribbled several pages of notes on the subject in 1691, and he had corresponded with the Swiss mathematician Nicolas Fatio de Duillier on it. In August 1693 Huygens wrote to the French mathematician Guillaume-François-Antoine, marquis of L'Hôpital, asking him if he knew the author of *De la Théorie de la manoeuvre des vaisseaux*; L'Hôpital replied the following month, stating that it was "M. Renaud [sic] who I know in particular and who is a naval engineer." Huygens quickly addressed what he saw was the critical flaw in Renau's analysis, and within a few days sent his analysis to Le Clerc, who promptly published it. In early 1694, an edition reached Renau, then in Brest overseeing construction of his ellipse ship *Bon*; a few days later he responded via letter, which was published a few months afterward in the pages of the Rotterdam journal *Histoire des ouvrages des sçavans*, shortly after Renau had returned from privating on the high seas.

The resulting back-and-forth debate over the *dérive* was carried out primarily by letter, both in print and privately, over the span of a quarter-century. This, the first and longest-running polemic in early naval architecture, was roughly divided into two periods: 1691–1696, principally between Renau and Huygens, and 1712–1714, principally between Renau and Johann Bernoulli. The following gives a brief chronology of the first debate:

1691: Huygens developed a theory of speed of ships and placement of sails.⁹⁵

1693: Le Clerc gave Huygens a copy of Renau's book.⁹⁶ Huygens exchanged letters with L'Hôpital,⁹⁷ then published his critique in *Bibliothèque universelle et historique*, titled "Remarque de M. Huguens sur le Livre de la Manoeuvre des vaisseaux imprimé à Paris en 1689" (Remark of Mr. Huygens on the Book *Manoeuvre des vaisseaux* printed in Paris in 1698).⁹⁸ This is the first time that Renau was publicly identified as the author of the book.

1694: Renau sent his response to Huygens ("Réponse de M. Renau à M. Huguens") and published it in *Histoire des ouvrages des sçavans*.⁹⁹ Huygens fired back his reply ("Réplique de Mr. Huguens à la reponse de Mr. Renau"), also in *Histoire*.¹⁰⁰ Renau wrote a private reply to Huygens, who published his response as a second letter in *Histoire* ("Raisons qu'a M. Huguens pour se plus continuer la dispute avec M. Renau").¹⁰¹ In late 1694, the entire exchange of printed letters was published by Estienne

Michallet.¹⁰² There was also a flurry of private letters involving Huygens and the mathematicians L'Hôpital, Fatio de Duillier, Gottfried Leibniz, Philippe de La Hire, and Johann Bernoulli.¹⁰³

During this time Renau's 54-gun *Bon* was completed; he took it to sea under a letter of marque and captured the 64-gun British East Indiaman *Berkeley Castle* off the Scilly Isles. Although he lost the prize cargo when the ship sank the next day, he managed to obtain a cache of diamonds, which he astutely gave to Louis XIV, who coveted them above all other gemstones, thus further cementing his position at the court.

1695–1696: Huygens died in July 1695 after a long illness. This should have ended the polemic; however, Jacob Bernoulli, writing on the shape of sails as catenaries, continued to argue in favor of Huygens,¹⁰⁴ as eventually did his brother Johann Bernoulli, switching his allegiances in private correspondence.¹⁰⁵ After 1696 nothing further was written on the subject.

This first phase of the debate over the *dérive* ranged over several different journals, undoubtedly making it quite difficult for all but the most careful reader of the day to follow and understand the arguments. Yet this form of polemical writing was the order of the day in the Republic of Letters; the arguments over the solid of least resistance and the priority debate over the calculus (described in chapter 3) would be carried out in a similar fashion. By one estimate, more than half of the articles published in some journals from 1675 to 1725 had to do with polemical exchanges, in which the authors took part in the debate or referred to it; almost nothing was written that was not immediately noticed and critically assessed by opponents.¹⁰⁶

So what was this particular argument about? In his first letter (1693), Huygens noted Renau's error in calculating ship speed, described in figure 2.9 (above). Huygen's argument, shown in figure 2.10 with a clarifying diagram, was that the semicircle BKG in Renau's diagram should not be a semicircle of speeds at different headings, but of the *resistance* at each heading; from this the speed could then be derived.¹⁰⁷ In Huygens's geometry, the ship speed $BS = v_1$ (at angle to sail β) is halfway between BG and KG, that is,

$$BS = \frac{BK + BG}{2},$$

which is an elliptical curve. Now, it is hard to understand Huygens's reasoning using geometry, so expressing it using trigonometry:

$$R_1 = R_{\max} \sin \beta, \text{ so } v_1^2 = v_{\max}^2 \sin \beta$$

$$v_1 = v_{\max} \sqrt{\sin \beta}, \text{ which is an elliptical curve.}$$

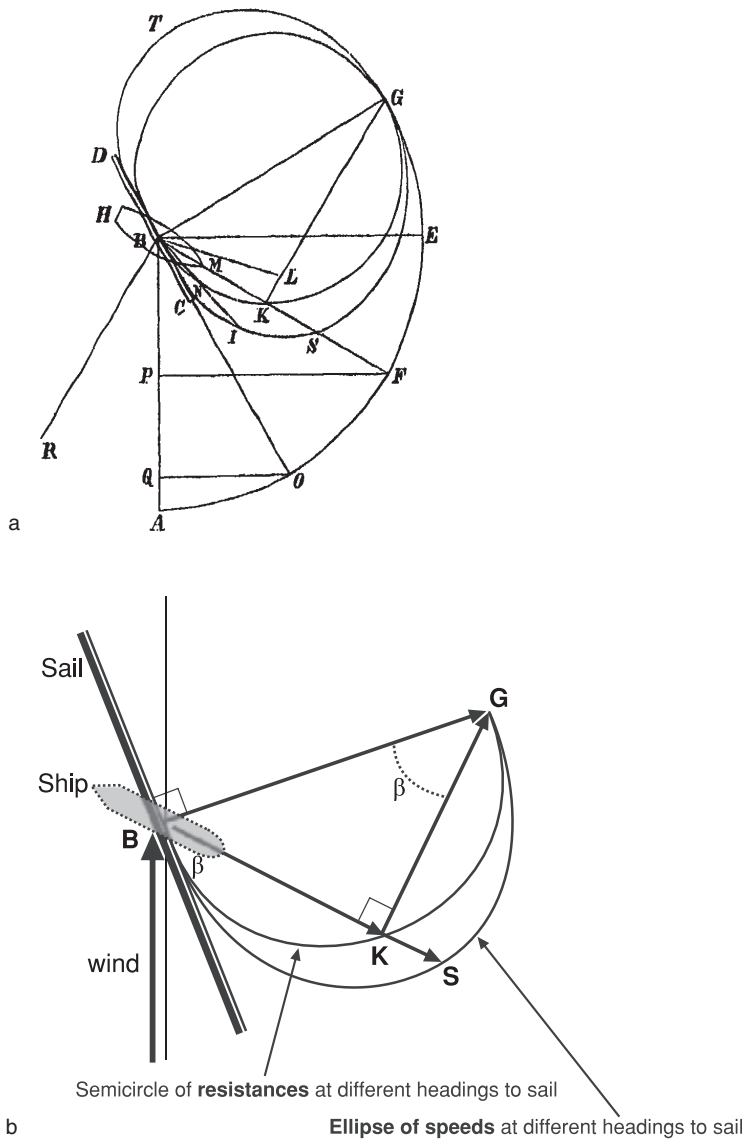


Figure 2.10

Huygens's diagram of ship speed and resistance. Top: Original figure. Bottom: Explanatory diagram. (Huygens, "Remarque de M. Huguens sur le Livre de la manoeuvre des vaisseaux imprimé à Paris en 1689" [1693/1905], p. 526). Credit: Bibliothèque Nationale de France/Gallica.

How does trigonometry compare with Huygens's geometric approach? Using $\beta = 45^\circ$,

$$v_1 = v_{\max} \sqrt{\sin 45^\circ} = 0.8409 v_{\max}.$$

For Huygens's geometric approach, note that $BK = 0.707BG$. Thus

$$v_1 = BS = \frac{0.707 + 1}{2} BG = 0.853 BG = 0.853 v_{\max},$$

which is close to the true value from trigonometry.

The practical difference between Renau and Huygens was that, according to Renau, a ship's speed at a heading of 45° to the sail was about 70 percent of its maximum speed, whereas Huygens argued that it was closer to 85 percent; in other words, Renau underestimated the speed of the ship.

Renau's "Réponse de M. Renau à M. Huygens" refuted Huygens's argument, claiming that a printing error had led to an apparent use of Pardies's misconception that resistance was proportional to speed, but that he had corrected it (this was the first time that Renau admitted being inspired by Pardies). Renau also defended the other aspects of his treatise by calling Huygens's suppositions into question. Huygens's "Réplique de Mr. Huguens à la réponse de Mr. Renau" was essentially an abridged version of his first article; Renau's private response in November 1694 repeated his original arguments in slightly different ways; and Huygens's "Raisons qu'a M. Huguens pour se plus continuer la dispute (Reasons That Mr. Huygens Has for Continuing the Dispute) simply stated that Huygens still did not agree with Renau.

Both Renau and Huygens had their supporters: Philippe de La Hire and Johann Bernoulli originally supported Renau, while L'Hôpital, Fatio, Leibniz, and Jacob Bernoulli generally sided with Huygens. Yet although mathematicians and constructors of the time closely followed the debate, apart from Jacob Bernoulli none of them continued the public discussions, and almost no further work was carried out on the subject for twenty years, with the exception of several complex and unmemorable analyses by the French mathematician Antoine Parent.¹⁰⁸ Even Paul Hoste, in his 1697 synthesis *Théorie de la construction des vaisseaux*, did not touch on the subject again. In the 1700s and 1800s, the first debate had a significant impact on scientific discourse, and was widely reported by mathematicians and historians, from the eighteenth through the twentieth centuries. Even the French philosopher Voltaire, with his usual acerbic wit, commented that the debate determined the most advantageous angle of the rudder; "but Christopher Columbus discovered America without ever suspecting that angle."¹⁰⁹ However, in terms of its impact on ship theory, the first debate paled in comparison with the short, sharp fight that occurred almost 20 years later.

The Second Period of the Debate (1712–1714)

The polemic with Huygens did no harm to Renau, for in 1699 he was nominated to the Academy of Sciences, presumably on the basis of his work on maneuvering. However, the War of the Spanish Succession, which began in 1701, led to another upheaval in Renau's already tumultuous career. As a well-known disciple of Vauban, he was sent to Spain to help rebuild its coastal defenses. However, during the battle of Vigo Bay in 1702, the British squadrons broke through his defensive chains and destroyed a large portion of the combined Spanish-French fleet. Despite this setback he continued working on the defenses around Gibraltar and Cadiz, now with the rank of lieutenant general, before returning to France in 1709.

Renau was a comparatively young 42 when he obstinately debated with Huygens, a superior mathematician. Now he was almost 60, and evidently had learned nothing from that experience. He again took up the question of the *dérive* and sought to answer several unresolved issues. Around 1712 he published a small (10 centimeters by 5 centimeters) book titled *Mémoire où est démontré un principe de la mécanique des liqueurs* (Memoir Wherein Is Demonstrated a Principle of the Mechanics of Liquids), where he restated and sought to clarify some of the original problems that Huygens had contested.¹¹⁰ Renau examined the acceleration of the ship due to the force of the wind on the sails, for the first time, elucidating in mathematical terms the concept of “apparent wind,” which (in simplistic terms) is the resultant of the true wind and the wind caused by the movement of the ship. His basic—and correct—argument was that the ship accelerated until the force of the apparent wind (a function of the squares of the wind speed and sail area) was balanced by the resistance of the ship in the water. But Renau got into exactly the same trouble in calculating those wind forces as he had in 1686 while calculating the resistance of a ship. He set up his problem with the velocities of true wind and ship wind at right angles, so that the apparent wind was the hypotenuse; but then he *thought* that he accounted for wind resistance by using the squares of the sides of the right triangle to derive the hypotenuse. In fact, he should have made the sides of the triangle the *squares* of wind speed to denote resistance, but his lack of understanding of trigonometry prevented him from seeing what, to modern eyes, was a very elementary error.

The little book received a neutral review in *Journal des sçavans*,¹¹¹ and it might have been summarily forgotten had not the French mathematician Pierre Rémond de Montmort, living near Paris, alerted Johann Bernoulli in Basel that Renau was planning a new book on the subject. Bernoulli had originally supported Renau's position to L'Hôpital during the first debates, although he subsequently changed his mind. He now took a close look at the 1689 text and found serious flaws, some of which Huygens

had not corrected. Bernoulli decided to treat the problem in the form of an essay, which was almost completed when Renau sent him his second book, asking for his opinion. In a private exchange of letters from June 1713 to December 1714, they argued the points back and forth, although Bernoulli apparently got the last word; very late in 1714, he sent his revised essay, along with some of the letters, to the publishers, and it was printed as *Essay d'une nouvelle théorie de la manoeuvre des vaisseaux* (Essay on a New Theory of the Maneuvering of Vessels).¹¹² It eclipsed Renau's second book, whose later ideas became generally known only via Bernoulli's interpretation. In terms of a work on ship theory, this was a best-seller; it can be found in many libraries even today, and was cited by Bernoulli's contemporaries as a jumping-off point from which new developments could be made. In 1727 Bouguer, explaining his plans for research into ship theory to Minister of the Navy Maurepas, declared that he could "push the matter much further along than the late Mr. Bernoulli."¹¹³

Bernoulli made several points in his *Essay*: the first, ironically, was that Renau (who had commanded several ships) erred by assuming that the *dérive* would be constant at all headings, whereas Bernoulli (a landlubber) correctly argued that it would change depending on the angles of the wind and sail; the second was that both Huygens and Renau miscalculated the way resistance and speed should be estimated. He described the curvature of sails filled by the wind (of which more later) and the lateral force on a curving ship's hull, and reprised the derivation of most efficient rudder angle from the v^2 and $\sin^2$ laws (arriving at $54^\circ 44'$, close to Renau's 55°). But Bernoulli's most important contribution was to describe Renau's error not in terms of geometry but in terms of vector diagrams and the parallelogram of forces. He described it this way (using figure 2.11):

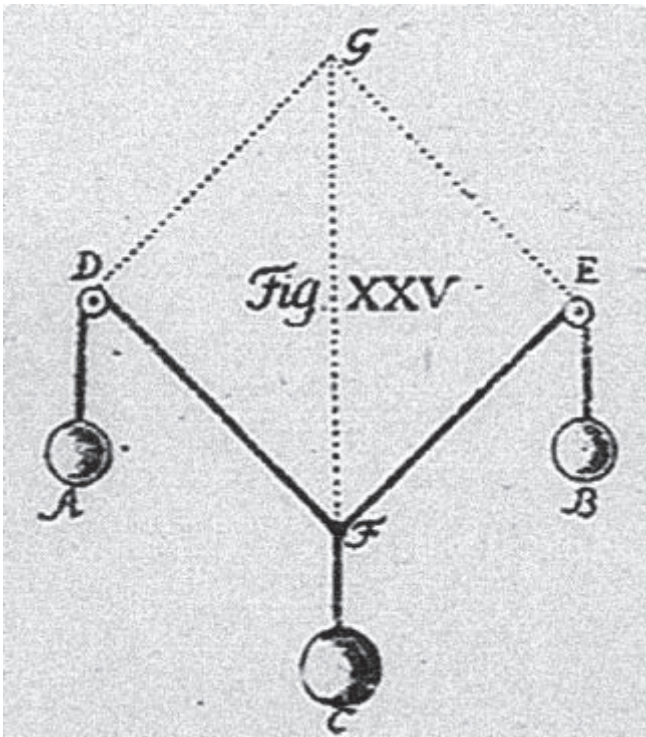
The weights A = 3 and B = 4 are balanced by a third weight, C. According to Renau's faulty analysis of force as a product of sail area and wind speed:

$$C = A + B = 7 \text{ (left, fig. XXV).}$$

In fact, the proper method of vectors would give the counterbalancing weight in terms of force proportional to the square of the wind speed; thus

$$C = \sqrt{A^2 + B^2} = 5 \text{ (right, fig. XXVIII).}$$

In the words of the science historian Pierre Costabel, this was a "magisterial lesson" from Johann Bernoulli.¹¹⁴ Yet this lesson was not limited to Renau; these were early days in the development of rational mechanics, and the laws of vector analysis had not been fully worked out (as described in chapter 3). Bernoulli's *Essay* was a pioneering example of this still novel representation of forces, and helped give rise to a



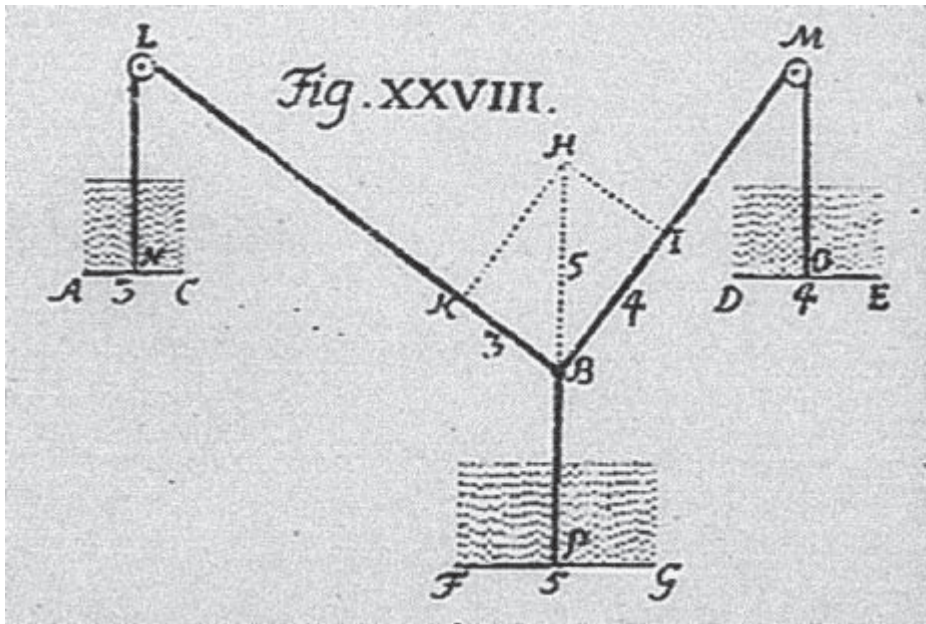
a

Figure 2.11

Bernoulli's explanation of the parallelogram of forces. Left: Renau's faulty use. Right: Bernoulli's correct use. (Johann: Bernoulli, *Essay d'une nouvelle théorie de la manoeuvre des vaisseaux* [1714]). Credit: Texas A&M University Library.

more complete investigation by Johann's son Daniel Bernoulli, whose 1726 memoir established the fundamental rules of vector analysis for forces.¹¹⁵

Renau did not take his arguments any further after Bernoulli's book came out. His thoughts turned far from ships and even from engineering. From 1715 to 1719 he tried, but failed, to instate Vauban's ideas of proportional taxation in the town of Niort, near La Rochelle.¹¹⁶ His health failed him, too, and he suffered from what his eulogy termed "retention of urine," which, given his age (67), was probably from an enlargement of the prostate, possibly due to cancer. The remedy proposed by Malebranche was to drink very large quantities of the spring waters at Pougues on the Loire River. According to his eulogy, Renau "almost drowned" from drinking too much water, and he died shortly thereafter, on 30 September 1719, in perhaps the first recorded instance of hyponatremia or overhydration, a condition that afflicts some marathoners today.¹¹⁷



b

Figure 2.11 (continued)

Applications of *Essay d'une nouvelle théorie de la manoeuvre des vaisseaux*

Once Bernoulli's *Essay* appeared, mathematicians lost no time in working out some of the applications of his theories. After writing an in-depth analysis of Bernoulli's book in the *Journal de Trévoux*, Antoine Parent set about solving some of the problems of the proper angles of rudder, sail, and keel that Bernoulli had posed.¹¹⁸ Jacob Hermann, a Swiss mathematician who would later influence Euler, demonstrated a principle of rational mechanics using the *dérive* in his monumental work *Phoronomia*,¹¹⁹ and much later the British mathematician Colin MacLaurin used Bernoulli's problems to explain the use of maxima and minima in vector analysis.¹²⁰ One enterprising instrumentmaker developed a device to automatically compute the angles of keel, wind, and sail to make these calculations possible.¹²¹

The most celebrated applications of Bernoulli's principles were developed by the French hydraulics engineer Henri de Pitot, soon to be known for his instrument to measure fluid velocity (see chapter 3). In 1727, he (like Parent) worked out general solutions for the correct angles of rudder, sail, and keel.¹²² He then published a series of practical applications to these solutions in a widely read book, *La Théorie de la manoeuvre des vaisseaux* (The Theory of the Maneuvering of Vessels), which brazenly

carried almost the same title as Renau's 1689 work and used precisely the same frontispiece.¹²³ But the book was nothing like Renau's; although filled with long equations, and using differential calculus to good effect, it provided a series of apparently useful tables that showed, for example, the sideways resistance of curved bodies according to their angle of *dérive*. In particular, he presented a series of tables to solve typical problems of navigation; for example, a ship sailing west-northwest with an east wind, having a *dérive* of 30°, would require the sails to be set at 75° to the line of the keel, which would give an angle of 83° to the wind.¹²⁴

A similar book, *Nouvelle Théorie de la manœuvre des vaisseaux à la portée des pilotes* (New Theory of Maneuvering for the Use of Pilots) was published in 1746 by Alexandre Savérien, an especially literate naval constructor.¹²⁵ Savérien criticized Renau and Huygens while lavishing praise on Johann Bernoulli and Pitot; however, he sought to correct several faults he found in Bernoulli's work regarding wind speed, and attempted to simplify Pitot's calculations and tables, in order to make the book (as the title indicated) useful to pilots.

These books should have come as quite exciting news for sea officers; here were scientifically developed instructions on how to properly trim, sail and maneuver ships. It is not clear, however, that these initial works had any impact on the formation and education of pilots or captains. Although some of Bernoulli's results were mentioned in practical texts on warfare,¹²⁶ they did not appear in any works on navigation or piloting. As would be the case for many other theoretical developments in naval architecture, only the later investigations of Pierre Bouguer would find their way into practical usage.

Maneuvering Theory and Naval Tactics

The principal features that marked the debate over the *dérive* from 1689 to 1714 were intense focus on the underlying principles of mathematics and physics; comparative lack of focus on real-world problems; and transnational participation (France, Netherlands, Prussia, and Switzerland). After Johann Bernoulli's decisive *Essay*, fundamental research into the mechanics of maneuvering theory was marked by a shift in emphasis to the solutions of more practical problems, and was limited principally to France.

These two defining features of the post-Bernoulli period were not accidental; France was rapidly becoming known as the leader in the development of naval tactics, begun by the work of Tourville and Hoste in the 1697 *L'Art des armées navales*. In particular, Hoste (a mathematician) sought to make tactical analysis into an exercise in geometry, a characteristic that would be carried through in French strategic thinking well into the 1800s. French sea officers in particular were highly trained in science and

mathematics, and the complex diagrams they used were closely modeled on Euclid; by contrast, British tactical thinking tended to be dominated more by practical considerations such as signals, rather than geometrical constructions of maneuvering. However, the difficulty in coordinating ships in a line of battle, the variability of wind and sea, and the length of time it took to execute even the simplest maneuvers meant that tactical theory had little to do with what actually happened in wars at sea.¹²⁷

But French scientists, notably Bouguer, devoted a considerable amount of effort to the mathematical analysis of specific problems in maneuvering. This was due mostly to the support they received from Minister of the Navy Maurepas and his successors to carry out research into naval matters, (more extensively treated in chapters 3 and 4). Bouguer's first work in this field was in 1732, with his Academy of Sciences paper on pursuit curves.¹²⁸ As the name implies, they are the curves that define the headings a chasing ship should assume to overtake another ship moving on a different course; Bouguer, ever practical, was demonstrating to pilots that they should not point their bows directly at the ship they were chasing, but rather lead the target, a principle known to any game hunter. Bouguer's colleague and rival Maupertuis also weighed in with a short paper aimed at simplifying Bouguer's work.¹²⁹ Bouguer further discussed maneuvering in his 1746 synthesis of naval architecture, *Traité du navire* (Treatise of the Ship).¹³⁰ Admitting that the subject was "thorny" due to the previous controversies, Bouguer launched into the various problems that had been treated before, such as the speed of the ship in a wind, the *dérive* with respect to the angle of the sail, the proper angle of sail for a given wind condition, and a reprise of the pursuit curves, deriving general solutions that could be applied to any particular problem. However, this section of the book was much less developed than the sections on resistance and stability, and Bouguer would return to more specific problems in the years to come.¹³¹

The Swiss mathematician Leonhard Euler was the next to weigh in on the subject in 1749, in his synthesis of naval architecture, *Scientia Navalis*, abridged in 1773 as *Théorie complète de la construction et de la manoeuvre des vaisseaux* (Complete Theory of the Construction and Maneuvering of Vessels).¹³² Euler carefully separated the hydrodynamic problem of controlling the ship by its rudder from the vector analysis of the sail angle and route of a vessel. Unlike Bouguer and his predecessors, who gave quasi-static formulas to calculate the most effective angles for given situations, Euler treated the rudder problem as one of rotational dynamics, examining both the inertia of a turning body and the force required to maintain the rudder angle. By contrast, his analysis of the problems surrounding the *dérive* was more in keeping with previous work, providing tables to show the correct angles of sail for required routes.

Not long after Euler's *Scientia Navalis* appeared, the Spanish constructor Jorge Juan y Santacilia wrote his own synthesis of naval architecture, *Examen marítimo, teórico práctico* (Maritime Examination, Theoretical and Practical). He added nothing substantial to the subject of the *dérive*, mostly repeating what Bouguer and Bernoulli had found.¹³³ However, he devoted great attention to the forces of wind on the sails and the speed of ships (which are briefly discussed later in this chapter and in chapter 3).

If Bouguer had somewhat neglected maneuvering in his *Traité du navire*, he made up for it by writing three French Academy of Sciences papers in three years, and subsequently a book that would synthesize the results of his previous work on maneuvering and add new material. The first paper, in 1752, was on the proper form of a ship that would easily obey the rudder, which was of course a tactical requirement for naval ships. The optimum “center of oscillation” (i.e., center of rotation) was determined using differential equations, such that the turning moment of the rudder was maximized and the resisting moment of the hull was minimized. The resulting hull shape looked rather like a modern airfoil.¹³⁴

In the next paper, in 1754, Bouguer addressed another tactical issue, the proper angle to set the sails in order to get maximum speed (as in a chase). Again making good use of maxima/minima differentials, he developed what would later be called the “double tangent rule” (i.e., the ship will go fastest when the tangent of the angle between the wind and the keel is twice that between the sail and the keel).¹³⁵ The third paper, in 1755, treated a more universal problem for ships, not just warships—how to get away from a lee shore (i.e., sailing away from a coastline toward which the wind is driving the ship). For this, Bouguer again employed a maxima/minima solution for the best sail angles to obtain maximum speed in a direction perpendicular to the course line.¹³⁶

But it was his 1757 synthesis, *De la Manoeuvre des vaisseaux* (On the Maneuvering of Vessels), published a year before Bouguer's death, that would do for ship maneuvering and operations what *Traité du navire* had done for ship construction: provide a general theoretical basis to calculate the performance of a ship before it was built, and offer guidance on the most effective forms of maneuvering, in lieu of repeated trial and error.¹³⁷ Bouguer directly cited Bernoulli's *Essay* as his starting point, and carefully separated this work from *Traité du navire* and other works of construction, and even from his recent *Nouveau Traité de navigation*, as a work intended to assist pilots and captains specifically in naval maneuvers. He was assisted by the naval captain Paul-Osée Bidé de Chézac, assistant director of the Academy of Navy, in developing the practical aspects of the book.¹³⁸ Like *Traité du navire*, it was divided into three books:

- Book 1: Basic concepts of mechanics and dynamics, including shock theory of resistance and friction; recapitulation of certain aspects of ship movement, such as the metacenter, pitch, and roll.
- Book 2: Action of the rudder; turning of the ship by sails; the best shape for a ship to obey the rudder; estimating the time for maneuvers; finding the center of rotation by experiment; the effect of added weights on rotation.
- Book 3: Real and apparent wind; the placement of sails to obtain greatest speed; calculating the *dérive*; considerations in the placement of multiple sails, including the “double tangent rule” for the best angle of sail.

De la Manoeuvre des vaisseaux brought together Bouguer’s previous work on masting (discussed in the next section), pursuit curves, and his three Academy papers, and added new material to round it out. He also provided practical means of determining theoretical quantities, as he had done in *Traité du navire* with the inclining experiment to determine the metacenter (discussed in chapter 4). For example, rather than performing the laborious calculations for the center of oscillation (center of rotation) of a ship, he devised an experiment to determine it. In figure 2.12 a ship in calm water is loosely moored fore and aft to a quay, and a heavy weight (here, a cannon) pulls the stern line so that the ship rotates. By measuring the rotation at each end (and repeating it with the cannon attached to the bow line), the center of rotation can rapidly be established.¹³⁹

De la Manoeuvre des vaisseaux quickly became the most influential book of maneuvering theory, although in truth there was no real competition. In 1764, the Venetian navy carried out Bouguer’s experiment for determining the center of rotation of the 64-gun *San Carlo Borromeo* (figure 2.13). *San Carlo*, completed in 1750 by the constructor Marco Nobile, was the subject of intense investigation by the Venetian navy to adopt it as the standard type for all first-rate ships; the hydraulics engineer (and navy “consultant”) Giovanni Poleni made numerous studies of the ship in the 1760s. As can be seen, the testing apparatus was almost identical to that proposed by Bouguer. The hoists placed on the quay were sufficient to let the cannon drop about 4 meters, inducing enough movement to allow the center of rotation to be estimated. The experiment was repeated by applying force to the mainmast and mizzenmast.¹⁴⁰ It is not known how the results of the calculation were used.

The following year (1765), a renowned captain in the Compagnie des Indes (East Indies Company), Jacques Bourdé de Villehuet, published *Le Manoeuvrier; ou Essai sur la théorie et la pratique des mouvements du navire et des évolutions navales* (The Maneuverer; or Essay on the Theory and Practice of Ship Motions and Naval Evolutions), the first

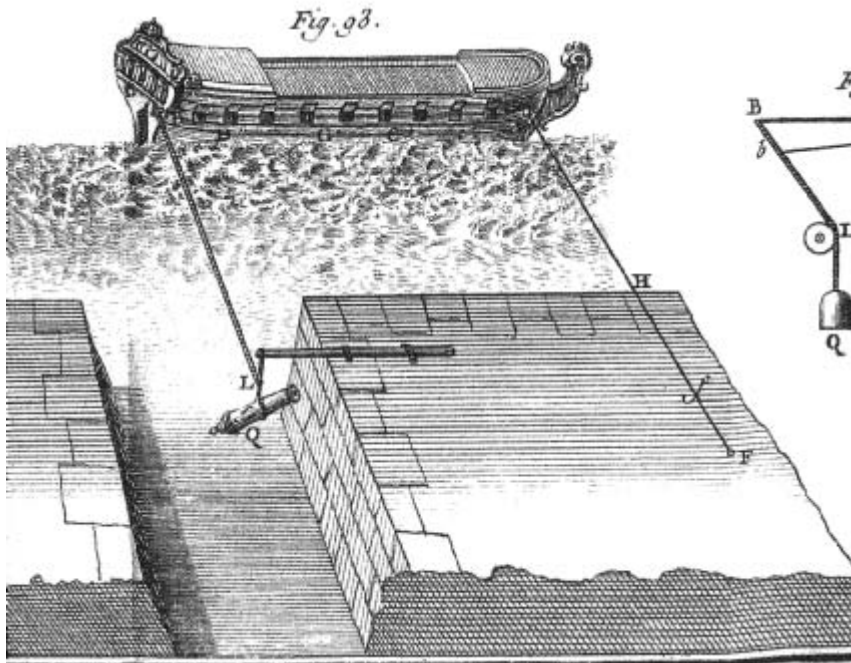


Figure 2.12

Bouguer's experiment to determine center of rotation. (Bouguer, *De la Manoeuvre des vaisseaux* [1757], plate X)

French book on naval tactics since Hoste's *Art des armées navales*.¹⁴¹ Bourdé de Villehuet incorporated many of Bouguer's ideas from *De la Manoeuvre des vaisseaux*, as well as other theoretical texts, such as those on proper lading of ships, into a textbook format. He rendered Bouguer's maneuvering theories accessible by incorporating simplified tables of results instead of long equations; this was similar to the approach that Duhamel du Monceau had used for naval construction when he adapted Bouguer's *Traité du navire* for his 1752 textbook *Éléments de l'architecture navale* (discussed in chapter 4).

These texts were aimed principally at pilots and sea officers, and formed a vital theoretical backdrop to their practical training, in much the same way that fighter pilots today are given extensive instruction in theoretical aerodynamics. *Le Manoeuvrier* was reprinted at least seven times in French, and was translated into Russian in 1774 and into English in 1788; it became the basis for two books by the noted British author David Steel (*Elements and Practice of Rigging and seamanship* and *Seamanship, Both in Theory and Practice*) that were published from 1794 to 1841. As noted by the historian of seamanship John Harland, Bouguer's "double tangent rule" (once again, that the

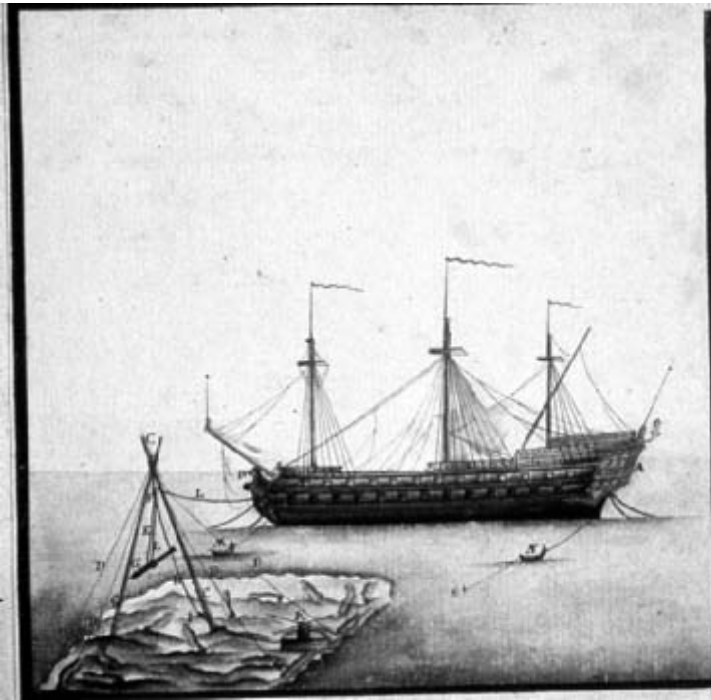


Figure 2.13

Center of rotation experiment on *San Carlo Borromeo* (1764). Credit: Archivio di Stato, Venice (PPA 535, negative 1717, print 198)

ship would go fastest when the tangent of the angle between the wind and the keel was double that between the sail and the keel), as well as other theories, were repeated verbatim by Steel, and found their way into books on seamanship and ship handling by Richard Gower (1808), Edmund Blunt (1824), John Murphy (1849), and Pierre-Marie-Joseph de Bonnefoux (1852), the last being published a century after the theory was introduced.¹⁴² Thus, it could be argued that the polemic Pardies had begun in 1673 endured for almost two centuries, perhaps one of the longest-running scientific debates in history, although the arguments over the shape of sails began earlier and lasted longer.

Sails as Curved Surfaces

The shape of sails as a mathematical surface was a minor but interesting sideline to the debate over the *dérive*, and is here covered only very briefly.¹⁴³ Christiaan Huygens had been working on the class of parabolic curves that would later be called the

catenary as early as 1646. He recognized that a sail, inflated by wind pressure along its flexible surface, would attain such a shape.¹⁴⁴ Pardies also recognized this fact in 1673.¹⁴⁵ It would not be until 1691 that Huygens, Leibniz, and Johann Bernoulli would each come up with the equation of the catenary (responding to a challenge by Jacob Bernoulli), each recognizing that it would apply to a sail.¹⁴⁶ Huygens and L'Hôpital debated the exact shape of the curve in 1693–1694.¹⁴⁷ Jacob Bernoulli subsequently wrote a series of papers on the shape of sails as caustic curves that appeared in *Acta Eruditorum* from 1692 to 1696, in which he also addressed the Renau–Huygens debate.¹⁴⁸ Johann Bernoulli would later use his brother Jacob's analysis of sail shape and force in his *Essay d'une nouvelle théorie de la manoeuvre*. The analyses of Jacob and Johann Bernoulli depended on three suppositions: the “shock theory” of force transmittal, where the impact is proportional to the sine² of the local angle of incidence; uniform horizontal force distribution across the sail; and vertical force distribution that varied as height above the water surface (i.e., equivalent to hydrostatic pressure).

Although Pierre Bouguer initially treated the shape of sails only very superficially in his *Traité du navire* (he considered them as flat planes), he analyzed it in more detail in *De la Manoeuvre des vaisseaux*, looking at both symmetrical and asymmetrical cases of wind loading; however, he treated the shapes as simple circular arcs.¹⁴⁹ Leonhard Euler was much more explicit in his analysis, treating the sails as flexible lines of indeterminate shape and developing the general equations of form for each.¹⁵⁰ Jorge Juan y Santacilia entered into the most detail, building on Euler's analysis but also providing equations to obtain an equivalent flat sail (using the model of children's kites as an example), to make wind force calculations easier.¹⁵¹

In none of these cases does the modern concept of pressure appear; instead, the shock theory of force (described in chapter 3), remained the accepted model. The sail was treated as something of a “wind bag,” and the most efficient angle of the sail in this model would be perpendicular to the wind. Even in works as late as the 1932 British *Admiralty Manual of Seamanship*, the explanation of the movement of ships against the wind used the same types of force diagrams as Pardies, Renau, and Bernoulli developed.¹⁵² Modern sailing theory, by contrast, compares a sail to an airfoil, with the lift due to the difference in pressures accounting for the driving force. Ironically, it would not be until the twentieth century that Bernoulli's famous laws would supplant the analysis that he had promoted two centuries before.

Masting of Ships

Perhaps one polemic in naval architecture can be considered even older than the debates over the *dérive* and sail shape: the proper placement of sails and masts to

achieve the greatest efficiency. Different cultures around the world found widely divergent solutions; the lugsails found on junks and sampans in East Asia, the lateen rigs of dhows in the Arabian Sea, and the square rigs of European ships were all perfectly adequate means of propelling ships. In northern Europe particularly, the number and size of masts (and sails) increased from the 1200s to the 1400s as trade routes grew longer, requiring ships of greater capacity that could operate efficiently on the open ocean.¹⁵³ These broad changes, and the hundreds of small improvements that accompanied them, were generally incremental and the result of educated trial and error; larger and more numerous sails gave greater speed, but that had to be balanced against the effects on stability, blockage of one sail by another, and the ability of the crew to handle an increasingly complex rig. That trial-and-error process is, to a large extent, how improvements in sails are made today. However, unlike today, there was little underlying theory to guide constructors in making these changes.

Aristotle, circa 330 B.C., had attempted to answer the question of why a higher mast makes a ship go faster, arguing through his principle of “virtual velocities” for levers, that mass times speed was the same on both sides of a fulcrum, so a higher mast meant a longer lever arm, thus giving greater speed.¹⁵⁴ Although mathematicians had largely disproved this idea by the 1600s (in fact, the increased “push” is due to greater wind speeds at higher altitudes, as one moves away from the surface boundary layer), the ideas of Aristotle were so tenacious that even as late as 1697, Paul Hoste was quoting him to support the notion that sail power was equal to the wind force times the speed of mast rotation.¹⁵⁵

1727 Academy of Sciences Prize on Masting and the *Point Vélisque*

Pierre Bouguer had caught the attention of the assistant director of the French Academy of Sciences, Jean-Jacques d’Ortous de Mairan, when in 1722 he assisted in a study of admeasurement of ships (described further in chapter 4). In February 1724, Bouguer presented the Academy with a treatise on the masting of ships, which Mairan and several other members examined.¹⁵⁶ They took their time, and in August, Mairan presented their findings to the Academy, in a careful analysis of Bouguer’s treatise “L’Art de mâter les vaisseaux 1^{re} partie” (The Art of Masting Vessels, 1st Part).¹⁵⁷ No copy of the original text is known to exist, but Mairan was quite detailed in his presentation, and clearly showed his admiration for Bouguer’s original thinking. Although Johann Bernoulli had not discussed masting per se in his *Essay d’une nouvelle théorie de la manoeuvre*, it appeared to be the last word on the general subject; for Bouguer, Bernoulli’s presence must have been palpable. But the young (22) hydrographer had very confidently struck out on a completely new line of inquiry, examining not speed and route, but the effect of the sails on the behavior of the ship, notably roll and pitch.

The broad outlines of the treatise, as described by Mairan, were as follows: the true cause of excessive roll and pitch is poor placement of the sail, that is, when the intersection of the force of the wind against the sail with the force of the water against the bow is not directly above the center of mass of the entire ship. This intersection of forces Bouguer termed the *point vélique* (roughly, “windage point”). If the *point vélique* is located too far forward or aft of the center of mass, the ship will be unbalanced and will move away from the horizontal position. Bouguer explained that there would be several *points véliques* for diagonal sailing as well, affecting ship roll. Although it would be possible to change the distribution of the mass of the ship, the easiest means would be to lay out the masts such that the *points véliques* fall directly over the center of mass. Bouguer concluded by stating that he was working on a method of calculating a bow that would always provide horizontal equilibrium, but that he had been stopped by the difficulty in integral calculus; he promised to provide answers in the second part of his treatise.

Since 1714 the French Academy of Sciences had offered annual prizes, the subject decided by committee. Mairan took the earliest opportunity to propose that the Academy choose the masting of ships as its topic; he also made certain that he would be one of the judges for the prize. In July 1725 the Academy announced that the subject of the prize for 1727 would be “the best method to mast the ship with regard to the number, height, and placement of the masts.” The first prize was 2,000 *livres tournois* (about \$13,600 in 2002), which Mairan fully expected that Bouguer would win. In every sense of the word, the contest was rigged.

The six entries (anonymous, as required by the rules) were received in September 1726, and the prizes were announced publicly on 26 April 1727 by André-Hercule de Fleury, the king’s prime minister; entry 2 won the prize, entry 4 received honorable mention (*accessit*), and entry 6 was simply noted as having competed (*concoureu*) for the prize; nothing is known of the other three entries. The judges of course knew that entry 2 was Bouguer’s, but probably did not know until later that entry 4 was by Leonhard Euler, then a rising Swiss mathematical protégé of Johann Bernoulli, or that entry 6 was the work of Charles Étienne Louis Camus, a young French astronomer and mathematician. Mairan, who had overseen Bouguer’s victory, could not wait until the official announcement, and hurriedly wrote to President of the Academy Jean-Paul Bignon on 20 April, to laud Bouguer’s efforts.¹⁵⁸ The three entries were to be printed immediately, but Bouguer requested time to put in an “Additions” section. He had undoubtedly known he would win, for on 12 February 1727—two months before the winners were announced—he had asked Maurepas to let him come to Paris to submit these additional points, and probably to attend the announcement as well.¹⁵⁹ The three

entries were published in a single volume in 1728, and reprinted in 1752 and 1753 in the collections of Academy prizes.¹⁶⁰

Camus would go on to be a distinguished professor of mathematics, and eventually taught young constructors in Duhamel du Monceau's School of Maritime Engineering, but in retrospect, it is easy to understand why his entry "*De la Mâturation des vaisseaux*" (On the Mastings of Vessels) was not given a prize or even an honorable mention. Unlike Euler or Bouguer, he did not present any "worked problems," and though he demonstrated some important insights, none of his analyses were rigorous. Camus began by recapitulating known theories of fluid resistance, and then calculated the center of resistance on flat geometrical figures such as rhomboids as well as on composite shapes to represent real ships. He then argued that the proper position for a single mast would be at the center of fluid resistance in the horizontal direction; but knowing that the point changes as the heading of the ship varies, he argued that the mast should be at a point slightly forward of amidships to account for rudder forces. His study of multiple sails was limited to ensuring that they did not block each other. His examination of the proportions of sails between ship types indicated some potential insight into the nature of ship stability (see chapter 4), but ultimately Camus did not provide a rigorous analysis of that subject, either.

Euler's diaries for 1726 indicate that the 19-year-old graduate student at the University of Basel prepared systematically for the competition, although at the time he did not appear to understand basic principles of Archimedes' hydrostatics.¹⁶¹ His memoir "*Meditationes Super Problemate Nautico*" (Thoughts on a Nautical Problem), was principally an analysis of the wind forces on curved sails, and how they were transmitted to the masts and, therefore, the ship.¹⁶² He resolved those forces into their proper vertical and horizontal components in order to develop the pitching moment (i.e., pushing the bow of the ship up or down).

Euler recognized the need to balance the pitching moment with the appropriate restoring moment to maintain an acceptable angle of trim, but without fundamental knowledge of hydrostatics, he was unable to define that restoring force.¹⁶³ Although he showed a good mastery of the mechanics of the problems, he did not yet demonstrate the profound insights that he would so spectacularly display in just a few years. Euler would later return to the balance of pitching and restoring moments when he had a deeper understanding of Archimedes' principles; this would become the basis for the work in 1735–1737 in which he developed his fundamental theories in the hydrostatic stability of ships (discussed in chapter 4).

Compared with the other two acknowledged entries, Bouguer's "*De la Mâturation des vaisseaux*" (On the Mastings of Vessels), as published, was a veritable mini-treatise on

the whole field of naval architecture, providing important precedents for his *Traité du navire*.¹⁶⁴ It was also twice as long as his competitors' submissions, understandable since he had been preparing it for at least four years, compared with their one-year deadline. The main body was 119 pages long, with another 40 pages of "Additions" that explained practical methods of calculations for real ships. The main part of the treatise was based on his "L'Art de mâter les vaisseaux," in which he gave very detailed explanations of his *point vélique*. As shown in figure 2.14, the *point vélique* (N) is where the line of wind force through the center of sail (S-K) intersects the line of bow force caused by the shock of the water (D-H). If, as in figure 1, the *point vélique* N is aft of the center of gravity Q, it will lift that end and trim the ship forward. Figure 3 shows how the reverse would be true for N forward of Q. Figure 4 shows the proper placement of the *point vélique* directly above Q.

Bouguer gave several methods to define the direction of bow force by treating the bow as an elliptical solid. He briefly looked at wind overturning and hydrostatic restoring forces for a ship in heel but, like Euler, did not yet have the full understanding of Archimedes that would lead to his invention of the metacenter. He also devoted a considerable amount of his treatise to calculating the wind forces on multiple sails where the wind was at an angle to the ship, developing several simplifying assumptions along the way.

The "Additions" section showed Bouguer's first insights for what would later become major portions of *Traité du navire*. For example, he showed how to calculate the center of gravity of the ship by dividing it into parallel slices, each of whose areas and centers could be approximated by further division into equal-width trapezoids. As discussed further in chapter 4, this would become the "method of trapezoids" that naval architects use to this day in the calculation of ship displacement. Bouguer also provided a practical method of determining the force of water on the bow, by dividing the bow of a real ship—the salt carrier *Saint Pierre* at Le Croisic—into flat panels.¹⁶⁵ This, plus his expansion on the solid of least resistance developed by the French mathematician Charles Reyneau, would form part of his later work on the bow of least resistance (described in chapter 3).

Among his more important conclusions, Bouguer argued against the then-current practice of calculating mast size as a proportion of length and beam. His observation, based on his own model tests, was that the scaling laws were completely different; the practice, he argued, resulted in masts that were too high, so that the *point vélique* was too far aft. He advocated lower masts but wider yardarms to provide the same sail area. As would mark his later work, Bouguer closely mixed theory and practice in developing his concepts, using only as much mathematics as was necessary.¹⁶⁶ Bouguer was a

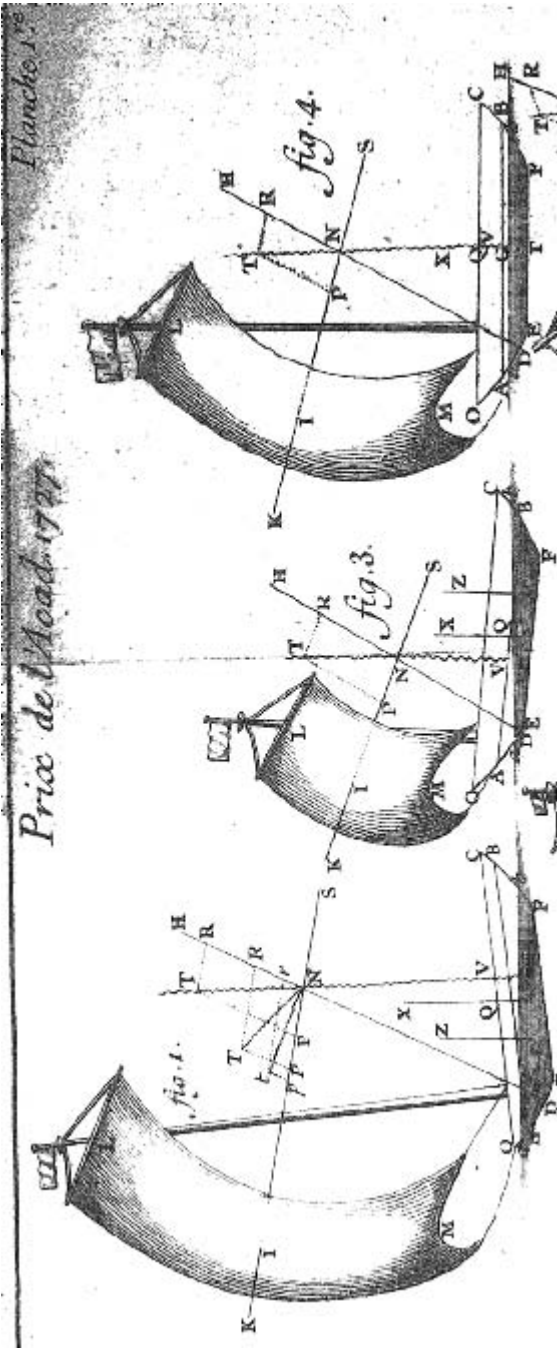


Figure 2.14

Bouguer's explanation of the *point vélique*. (Bouguer, "De la Mâtüre des vaisseaux" [1727], plate 1). Credit: Texas A&M University Library.

teacher of hydrography first and foremost, and well understood the need to present clear explanations that could immediately be put into practice. It was undoubtedly this facility to provide practical solutions that soon endeared him to Minister of the Navy Maurepas.

Practical Application of the *Point Vélisque*

Bouguer's theories were almost immediately taken up by a naval captain, Raymond Renault, count of Radouay, who in 1731 proposed to reduce mast heights and widen the yardarms of navy ships. He was given the opportunity to try out the system in 1733 on the 60-gun *Triton*, whose freeboard to the gun ports was too low and was in need of overhaul anyway. The new system was adopted as a part of an overall attempt to decrease the weight of the ship, including reducing the number of guns to 48; according to Radouay, reducing the mast heights would also prevent the ship from trimming too far forward and immersing the gun ports.¹⁶⁷

The trials were a success, and the ship fought during the Baltic campaign of the War of the Polish Succession, yet the French navy did not adopt the system; a similar suggestion of lowering the masts and widening the yardarms, made in 1765 by Bourdé de Villehuet, was also rejected.¹⁶⁸ This did not mark intransigence on the navy's part; in fact, the French navy was similar to other navies in encouraging a degree of experimentation with sailing rigs, but ultimately it left that choice to the experience of the ship's captain, who as often as not would elect to modify it from its original configuration.

Controversy over the *Point Vélisque*

Bouguer essentially repeated his *point vélisque* theories in *Traité du navire*, providing practical examples for actual ships and incorporating his metacentric theory of stability into some of the calculations.¹⁶⁹ However, just before the book went to the printers in early 1746, Bouguer was stung by a remark in Savérien's newly published *Nouvelle Théorie de la manœuvre des vaisseaux*, which criticized his assumption that the ship's center of gravity was the point of rotation during roll and pitch. Bouguer hastily added a note to his book before it went to final publication, explaining that his assumptions were firmly based in the late Johann Bernoulli's work.¹⁷⁰ Savérien quickly wrote and published a new book, *La Mâture discutée et soumise à des nouvelles loix* (Masting Discussed and Submitted to New Laws), that disputed Bouguer's theories (but also included Bouguer's responses to him via letter).¹⁷¹ Savérien's arguments can be summed up as follows:

- The center of gravity of the ship is not its center of rotation.
- The actual center of rotation is not fixed, but moves as the ship pitches and rolls; he calls this the “spontaneous center of rotation.”
- The actual “center of effort” for the mast is the common center of the arcs that the ship and mast make while pitching.

Savérien’s arguments were made without any equations, and Bouguer did not reply satisfactorily to his assertions; he simply repeated his original principles, and said that it did not matter whether the center of rotation was at the center of gravity or at some other point. Nevertheless, Savérien showed remarkably advanced insight in stating the principle that the center of rotation moves as the ship rolls and pitches. Modern sea-keeping theory uses dynamic analysis to estimate these movements; in general, the centers of pitch and roll are close to the center of flotation (i.e., the geometrical center of the water plane) at any given moment, which shifts as the shape of the waterlines changes due to the motion of the ship. Bouguer, in an Academy of Sciences memoir written the following year,¹⁷² repeated his replies to Savérien’s arguments, then went on to discuss the dangers of wind gusts on the sailing rig, arguing that it would be too difficult to analyze the problems on a purely scientific basis; rather, it required the knowledge and experience of sailors.¹⁷³

In 1747 the Swedish Academy of Sciences was asked by the Secret Defense Committee to investigate the proper position of the *point vélique* (which they termed the “center of equilibrium”). Pehr Elvius, the secretary of the Academy and a noted mathematician and astronomer, reported that contrary to current theory (Bouguer was not mentioned by name), the balance of four forces—wind, water against the bow, weight, and buoyancy—required the *point vélique* to be aft of the center of gravity, though both the center of gravity and the *point vélique* would need to shift forward as the ship gained speed. In order to sail close-hauled, Elvius argued, the *point vélique* would need to be at the center of the ship for best performance.¹⁷⁴

Although in hindsight, Savérien’s objections to the *point vélique* were correct, and Elvius found difficulties with the concept as well, neither man offered an adequate competing theory. Even Leonhard Euler, in his *Scientia Navalis*, essentially left behind his 1727 prize entry and expounded on Bouguer’s theory.¹⁷⁵ The idea of a point in space where two forces intersected was so easy to comprehend that it captured the imaginations of constructors and sailors alike. The term *point vélique* is still used today by French sailors, though it has come to mean the center of effort of the sails, and even has the literary connotation of a “focal point.”¹⁷⁶ The term as Bouguer defined

it (in English, the “velic point”) was used in books on seamanship and ship handling by David Steel (from 1794 to 1841), Richard Gower (1808), and others as late as 1848.¹⁷⁷

Incorporating the *Point Vélisque* in Design

Bouguer’s works introduced a number of novel concepts in naval architecture, such as the *point vélisque* for sailing quality, the ratio of bow resistance for speed, and the metacenter for stability. These last two quantities were highlighted in Duhamel du Monceau’s textbook *Éléments de l’architecture navale*, and they were subsequently required to be calculated for new ships by the ordinance of 1765 under Minister of the Navy Choiseul. Yet for unknown reasons, the *point vélisque* calculation was left out of both.

The actual calculation of the *point vélisque* was very time-consuming for French constructors, although much of it was based on the computations they were already doing to obtain the ratio of bow resistance (see chapter 3 for details). A memoir on the subject written in 1789 by Antoine-Jean-Marie, count of Thévenard (a navy captain who in 1769 had conducted model tests on resistance), took 84 pages to show how tortuous the *point vélisque* calculations could be.¹⁷⁸ Figure 2.15 shows the process for this calculation. The constructors would have to calculate, for each flat panel of the bow, the horizontal and vertical components of fluid “shock,” and then derive the mean line of bow resistance (M–N and P–Q). They would then calculate the center of sail area based on two or three of the major sails spread on each mast (line L–B in figure 4). The intersection of the two lines of force showed the location of the *point vélisque* (V), which could be compared with the longitudinal center of gravity (LCG) of the ship, to determine which way the masts and sails had to be moved in order to place the *point vélisque* directly above the LCG. In fact, in that era it was almost impossible for constructors to accurately estimate the position of the center of gravity (this will be discussed in chapter 4), nor were there experiments to validate the position of the *point vélisque*; thus the effort was really just an academic exercise.

Nevertheless, at least some French constructors undertook the effort as part of their design exercises; for example, François Guilleme Clairin-Deslauriers and Jean-Denis Chevillard included estimates of the *point vélisque*, *dérive*, and speed of the ship compared with wind in proposals for 64-gun ships submitted in 1765 and 1768.¹⁷⁹ But the practice was not universal among French constructors, and it probably was not consistently taught; for example, the standard textbook on masting used by students at the School of Student Engineer-Constructors of the Navy, *Traité élémentaire de la mâturation des vaisseaux* (Elementary Treatise on the Masting of Vessels), by Pierre Forfait, made

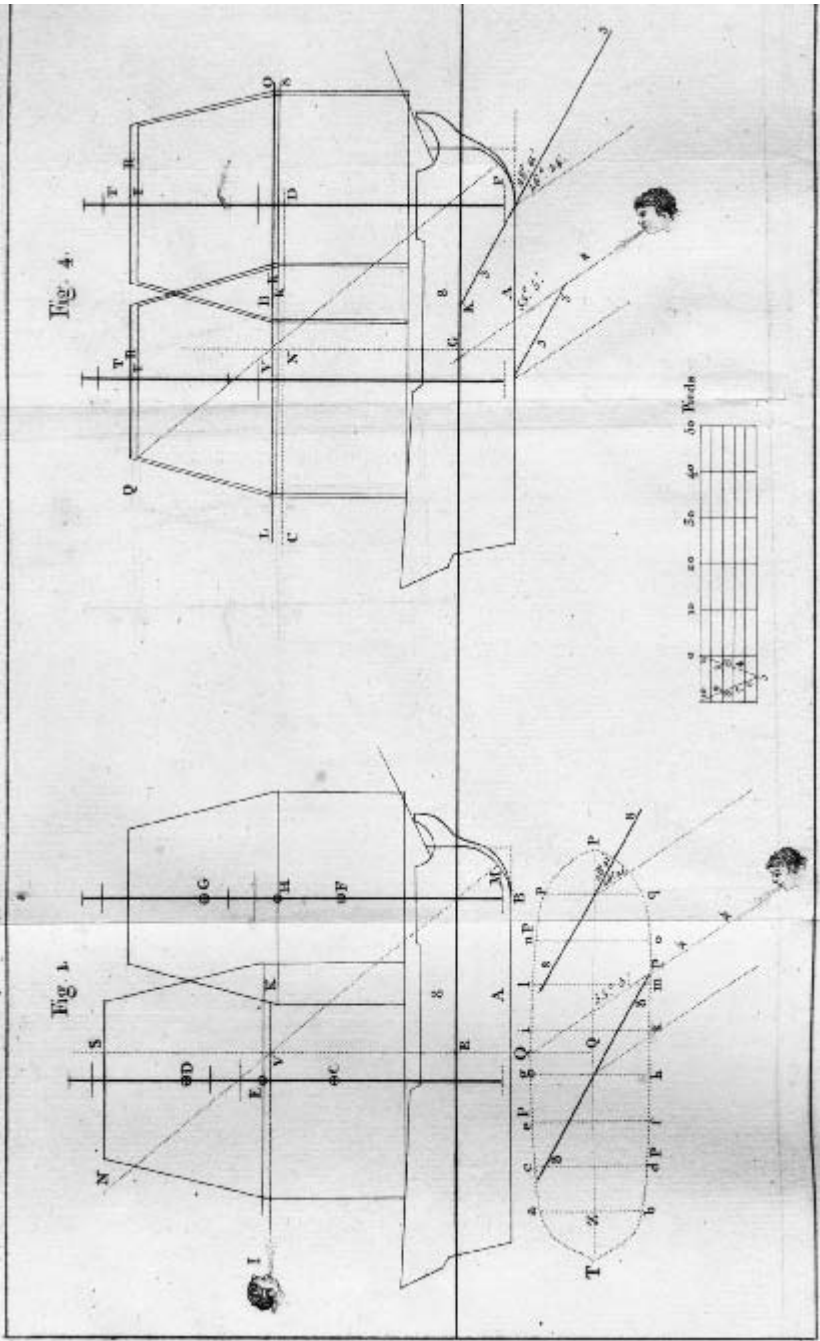


Figure 2.15
Calculation of the *point vélique* in practice. (Thévenard: *Mémoires relatifs à la marine* [1800], vol. 1, plate 1). Credit: Mariner's Museum, Newport News, VA.

no mention of the *point vélique* or, indeed, of any theoretical work by Bouguer and his contemporaries.¹⁸⁰

It is not clear precisely when or why the *point vélique* began to appear on the plans of French sailing warships, and I have found no indications of it on any plans from other European navies. My examination of comprehensive secondary sources, especially Jean Boudriot's definitive books *La Frégate dans la marine de France* (The Frigate in the French Navy), *Les Vaisseaux 50 and 64 canons* (The 50- and 64-Gun Vessels) and *Les Vaisseaux 74 à 120 canons* (The 74-to-120-Gun Vessels) do not show any plans indicating the *point vélique* before 1800. Only after 1810 have I found the *point vélique* calculated on ships such as the 60-gun *Uranie*, the 74-gun *Alger*, the 80-gun *Duquesne*, and the 100-gun *Hercule*, the last built in 1836.¹⁸¹ However, in none of those cases is the LCG of the ship indicated, meaning that the assumed effect on sailing performance could not be estimated from the information provided. I have found no indication of a *point vélique* in any plan from 1845 onward, when mixed sail-and-steam ships began to be integrated into the French fleet. It would appear that the *point vélique* faded from memory only when the wooden sailing ships had begun to be replaced by iron and steam.

3 A Shock to the System

“Science, great, mighty and in the end unerring,” replied my uncle dogmatically, “science has fallen into many errors—errors which have been fortunate and useful rather than otherwise, for they have been the steppingstones to truth.”

—Professor von Hardwigg in Jules Verne’s *A Journey to the Center of the Earth* (1871), p. 187

Professor von Hardwigg was not speaking about hydrodynamics in Verne’s novel, but his observation is nonetheless pertinent to it. From the modern perspective, its history is littered with false starts, unworkable results, and missed opportunities; some patently false theories took almost a century to be finally discredited. Yet, as Verne pointed out, the act of finding the errors in the theories eventually led to a series of laws that, in this case, proved useful in both civil and naval architecture.

This chapter traces the development of ship hydrodynamics within the framework of *rational mechanics*, the mathematical basis for mechanical and physical actions, a term coined by Newton himself.¹ It begins by explaining some of the key theories of rational mechanics, and discusses the small but vital role that ship theory played in its development. The chapter then describes the early notions of hydrodynamics, which were quickly supplanted when Newton’s fundamental work *Principia* (1687) introduced the “shock” theory of resistance and the solid of least resistance, both of which would dominate ship hydrodynamics in the 1700s. It outlines the early development of these ideas and their use in ship design in the mid-1700s. But by this time, hydrodynamic theory was already evolving away from the notion of shock toward that of streamlines and pressure, while increasingly sophisticated experiments with towed models also showed Newton’s theories to be wrong. By the end of the century, shock theory and the solid of least resistance were discredited. But the perception in Britain that those theories gave French constructors a decided advantage spurred the formation of the Society for the Improvement of Naval Architecture in 1791,

instigating an important series of experiments that would eventually lead to William Froude's work in the 1870s.

Rational Mechanics and Ship Theory

The earliest studies of the “science of waters” concerned not ships but rivers, canals, and lagoons, in part to support the increasing requirements for waterborne trade and land reclamation.² Even the laws of hydrostatic pressure developed by the Flemish engineer Simon Stevin and the French philosopher Blaise Pascal found no real use in ship theory until the nineteenth century. The only hypothesis derived from Newton's massive *Principia Mathematica* (Mathematical Principles) that directly related to ships was the “shock” or impulsion theory of fluid resistance, and its corollary, the solid of least resistance. The acceptance and evolution of shock theory and the solid of least resistance, and the subsequent “shock” within learned societies as those theories unraveled, tracked the rise and fall of many theories during the long development of rational mechanics. At the time, however, there was no real separation of mathematics from mechanics; and the men developing integral and differential calculus were also solving the problems of planetary orbits, tides, vibrating strings, ballistics, column buckling, and resistance of fluids. Ship theory played only a small—but strategically vital—part in the overall development of rational mechanics.

Concepts and Conflicts in Rational Mechanics

Rational mechanics, like most disciplines, initially developed via a series of contradictory theories and opposing camps. Several arguments that bore on the development of ship theory during the 1600s and 1700s were virtual displacements, vortices or attraction, live forces, center of oscillation, and vector composition of forces.³

Virtual Displacements The mechanics of Archimedes of Syracuse (circa 220 B.C.) were a stark contrast to the philosophies of Aristotle a century before. Though Aristotle explained his ideas in vague, subjective terms, his mathematical proofs are considered elegant even by today's standards. Yet Aristotle's *Mechanics* found a home within the doctrine that the Dominican friar Thomas Aquinas developed for the Roman Catholic Church in 1200s, and was used unchanged in catholic (especially Jesuit) schools until the mid-1700s, while the works of Archimedes did not begin to become widely accepted until the late 1600s, and then only after serious debates with followers of Aristotle.

One important debate was whether “virtual displacements” or “virtual velocities” was the correct measure of work, using the principle of the lever as the method of demonstration. Aristotle argued, qualitatively, that mass times speed (Mv and mV) was the same on both sides of a fulcrum (which is why he believed that sails mounted higher on a ship moved the ship faster, because the longer lever arm gave more speed).⁴ However, Archimedes, in his treatise *On the Equilibrium of Planes*, gave geometrical arguments that mass times distance (Ml and mL) is equivalent. A comparison of the two is given in figure 3.1. Archimedes’ lever law was further developed in 1608 by Simon Stevin, and in 1717 by Johann Bernoulli, in what is now called the principle of virtual work: the work done is equal to the force multiplied by the virtual (i.e., infinitesimally small) displacement through which it acts. But Aristotle’s ideas hung on for some time; as will be discussed in chapter 4, the French Jesuit mathematician Paul Hoste in 1697 erroneously argued that the ship’s stability was a function of the wind-on-sail force times the speed of the mast rotation, an idea not corrected until almost a half-century later.⁵

Vortices or Attraction A central debate in rational mechanics, which would polarize scientists along national lines, was the principle by which bodies moved and gravity was created. In 1644, the French philosopher René Descartes proposed—by analogy with bodies floating in fluids rather than mathematical proof—that the universe was filled with ether set into a vortex motion carrying the planets, stars, and comets, and, through its swirling action, creating gravity (figure 3.2). By contrast, Newton’s *Principia Mathematica* argued—through rigorous mathematical proofs—that gravity was a mysterious attractive force that acted at a distance, with no physical mechanism for transmission; in particular, Newton showed that actual planets moved more slowly than Descartes’s vortex laws would predict.

Through the early 1700s, the debate was political more than scientific; British scientists supported Newton, while those on the Continent—the French Academy of Sciences in particular—supported Descartes as a matter of national pride, even in the

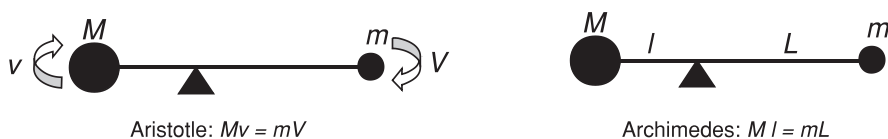


Figure 3.1

Lever laws of Aristotle and Archimedes.

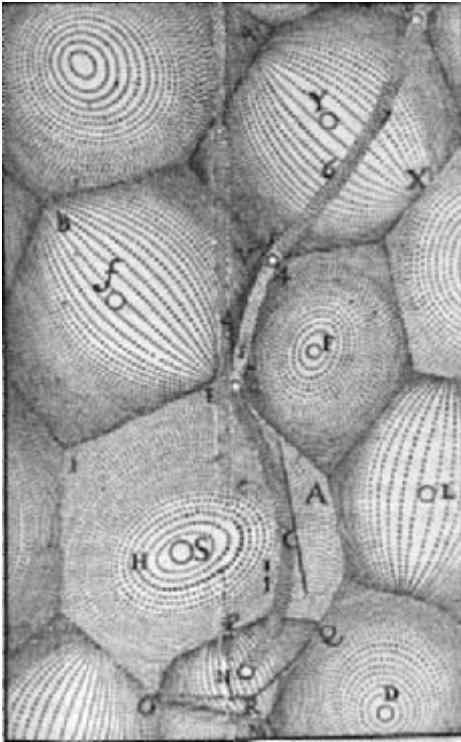


Figure 3.2

Descartes's planetary vortices (S = sun). (Descartes, *Principia philosophiae* [1644], p. 153). Credit: Bibliothèque Nationale de France/Gallica.

face of mounting experimental evidence that Newton had it right. This resulted in a stream of Academy memoirs and prizes that attempted to merge Newtonian mechanics with Cartesian vortices. Into this fray stepped the young hydrographer Pierre Bouguer. A skeptical Cartesian, he published a memoir in 1733 that examined the inclination of planetary orbits, using both vortex theories and gravity. It appeared just at the time scientists were casting about for a proof of one theory over the other. That proof involved the rather minor aspect of Descartes's theory, which stated that the vortices which spun the Earth would cause it to shrink at the equator and lengthen at the poles (a prolate spheroid). Newton, however, predicted that the centrifugal force of the spin would bulge the Earth at the equator and flatten it at the poles (an oblate spheroid). Thus, determining the correct shape of the Earth would validate one or the other model, and Bouguer's tentative entry into the debate helped land him a position on the Geodesic Mission to Peru.

Still, the vortex theory died slowly, although it never went beyond the planetary model. None of the scientists at the time applied the fluid vortex as a model for hydrodynamics, and for good reason; in Descartes's concept, fluid vortices carried bodies around rather than offering opposition to their motion, as Newton showed, so a mathematical analysis of resistance would not have been possible. In fact, it was not until the nineteenth century that fluid vortices came to be understood in mechanical terms.⁶

Live Forces Another dynamics controversy begun by Descartes was in the conservation of forces. Descartes believed that the product of mass times speed (later refined as the vector quantity velocity) mv was constant in the universe, and would be conserved in any reaction—for example, during the rebound of two colliding spheres. The German mathematician Gottfried Leibniz argued in 1686 that it was the quantity mv^2 , which he later called *vis viva* (live force), that was conserved during all physical processes such as collisions or by falling bodies; in this he was supported by impact experiments conducted by the Dutch physicist Christiaan Huygens. However, Newton's laws did not explicitly call out the mv^2 quantity; so, echoing the “vortices or attraction” polemic, the controversy over *vis viva* became divided along both theoretical and national lines, with German and Dutch scientists supporting Leibniz and Huygens, while French and English scientists sided with Descartes and Newton. It was only through later work by scientists such as Daniel Bernoulli in the 1730s that scientists began to understand that *both* laws were correct and entirely independent for specific actions. The conservation of mv (momentum) is applicable to all collisions, both elastic and inelastic, while *vis viva* would become known in another form as conservation of potential and kinetic energy, applicable in elastic collisions as well as in fluid dynamics.

Center of Oscillation An early result of the *vis viva* investigations was the determination of the center of oscillation of a multiple-pendulum system, which led directly to the development of the formula for the second moment of inertia. In 1673, Christiaan Huygens, a skilled clockmaker, published *Horologium Oscillatorium* (The Pendulum Clock), which contained several fundamental principles of pendulum theory, including how to find the center of oscillation of a system of linked pendulums in order to determine the period of the whole system. His beginning assertion, “When any number of weights starts to fall, the common center of gravity cannot rise to a height greater than that from which it starts” (figure 3.3), was a restatement of the *vis viva* laws.

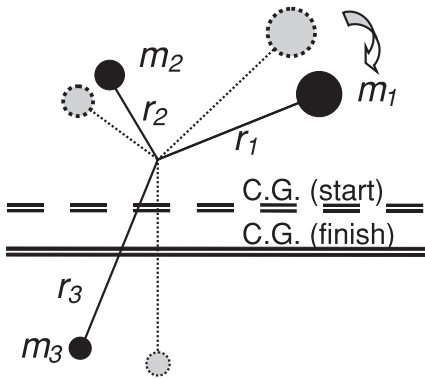


Figure 3.3

Multiple pendulums and center of oscillation.

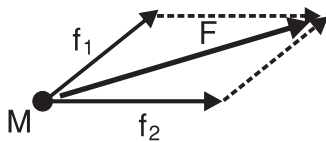


Figure 3.4

Vector composition of forces.

Huygens assumed that the height of return of each pendulum was proportional to the square of its velocity during its descent (mv^2), then showed that the entire system can be represented by a single equivalent pendulum with weight $M = \Sigma m$ (that is, $m_1 + m_2 + m_3 \dots$) and a length R (the center of oscillation of the system), given by the formula $MR = \sqrt{\Sigma mr^2 / \Sigma m}$. In modern terms, Σmr^2 is the second moment of inertia, a formula central to all modern study of dynamic systems. From 1686 to 1703, Jacob Bernoulli studied the same problem using the principle of the lever, and arrived at the same solution for the second moment of inertia and equivalent pendulum for a multiple-mass system. Bernoulli's results were probably the inspiration for the studies in the 1730s and 1740s by Pierre Bouguer, Leonhard Euler, and Daniel Bernoulli on the oscillation of ships, in which they modeled the ship as an equivalent pendulum, using the second moment of inertia formula (described further in chapter 4).

Vector Composition of Forces Simon Stevin first demonstrated, in 1608, the use of graphical analysis to show (see figure 3.4) how forces f_1 and f_2 that act upon mass M can be resolved into a single resultant force F , whose magnitude and direction can be

resolved geometrically. This principle would be demonstrated mechanically by the French mathematician Gilles Personne de Roberval, and mathematically by Newton and the French physicist Pierre Varignon. Although by the early 1700s it was a clearly enunciated concept, it was still subject to misinterpretation; as described in chapter 2, part of the 1712–1714 dispute between Bernard Renau d’Elizagaray and Johann Bernoulli revolved around Renau’s incorrect decomposition of sail forces. Bernoulli’s representation of these forces, not in terms of simple geometry but in terms of the vector composition of forces, was a step forward in explaining its proper use. Johann’s demonstration probably influenced his son Daniel Bernoulli, whose 1726 memoir established the fundamental rules of vector analysis for forces.⁷

These polemics represented only a small portion of the massive series of investigations that were carried out between 1680 and 1790. Mechanics and mathematics became inextricably linked as methods of analysis were developed to solve the problems of the day; for example, partial differential equations were developed in response to the problem of vibrations of an elastic string. Much of the work in developing rational mechanics was done by members of three academies: Paris, Berlin, and Saint Petersburg.

However, the person most responsible for tying together the various threads was the brilliant Swiss polymath Leonhard Euler (figure 3.5). The son of a pastor, Euler was tutored in mathematics by Johann Bernoulli, and became close friends with his son Daniel, working with him as he started his career in 1730 at the Saint Petersburg Academy of Sciences. That career would span 50 years, during which time he completely changed the landscape of mathematics and rational mechanics. Even today it is hard to comprehend his vast output, spanning over 100 volumes that, when stacked, are two stories high.⁸ He produced this enormous body of work despite numerous distractions and handicaps, including 13 children, a partial loss of eyesight in 1740, and complete blindness by 1767. His work was further interrupted by a move in 1741 to what would become the Berlin Academy of Sciences (at the request of the Prussian king Friedrich II), and in 1766 a return to Saint Petersburg.⁹

Although hydrostatics and fluid mechanics did not figure into Euler’s original program of work in rational mechanics, he transformed them the way he transformed almost every field he touched. In particular, he developed a general set of equations for idealized fluid motion, based on his derivation of Newton’s laws, that served as the jumping-off point for almost all models that would subsequently be developed.¹⁰ Ship theory was evidently attractive to him; his first major published work was his 1727 prize entry on masting, followed in 1749 by his monumental *Scientia Navalis* (Naval Science) and later by memoirs on propulsion, ship motions, and



Figure 3.5

Leonhard Euler. Pastel by Emanuel Handmann (1753), Kunstmuseum, Basel. Credit: Kunstmuseum, Basel, Martin Bühler (accession no. 276).

maneuvering.¹¹ However, measured against the backdrop of his other accomplishments, Euler's work on ship theory was of relatively minor importance.

Ship Theory in Rational Fluid Mechanics

In fact, the relative unimportance of ship theory in Euler's massive body of work reflects the fairly minor role it played in the overall development of rational mechanics. However, ship theory was seen as strategically vital by political figures—notably the French navy ministers Colbert and Maurepas—as a means of augmenting the effectiveness of individual ships as a counterbalance to the superior numbers in

the British navy. The support offered by the French Academy of Sciences in this research is a good case in point.

In 1714, Jean Rouillé, count of Meslay, a counselor in the Parliament, left a bequest of up to 4,000 *livres tournois* annually (about \$27,000 today) to the Academy of Sciences, for prizes to be awarded for memoirs on mechanics and physics. In the 1780s, the Academy of Sciences developed further prizes for machines, and other academies in France (e.g., Toulouse) proposed similar prizes. The academies were funded by the French government as a means of using scientific investigations to support policy; in this sense, these prizes were a sort of research contract proposed by the government through the intermediary of the academies. About 80 Rouillé de Meslay prizes were proposed between 1720 and 1792, of which 22 concerned fluid mechanics and maritime subjects. Of these, nine prizes directly addressed theories of ships or their component parts, and five of these were on the subject of rolling and pitching. Compared with other subjects, such as astronomy, ship theory accounted for a proportionally high number of prizes, which may be partially explained by the Academy's proximity to the school for naval constructors (discussed in chapter 5). In addition to the prizes, the government funded the Academy of Sciences to sponsor direct research projects including the 1775 model basin tests conducted by Condorcet and Bossut (discussed later in this chapter). The generous level of government support for fluid mechanics research, in particular that of ship theory, directly reflected the strategic and political importance attached to it.¹²

Even so, the total work devoted to ship theory represented only a small fraction of the overall program of rational mechanics, even when looking specifically at rational fluid mechanics. A comprehensive survey of the field of rational mechanics can be found in *Reuss's Repertorium*,¹³ a 16-volume index of all journal literature published by European scholarly societies from 1600 to 1800. Volume 4 (physics) and volume 7 (mathematics, mechanics, hydraulics, etc.) cover the range of works dealing with rational mechanics. An analysis of the works classed under the headings of hydrostatics, hydrodynamics, and naval science is given in table 3.1.

It is apparent that the published works dealing with ship theory accounted for only a small fraction of the total. Almost half of the works—on canals, rivers, pumps, mills, and general hydraulics—came under “hydrotechnics” (today we would call it “civil engineering”), and were often written by those actively involved in such hydraulic projects such as canal-building, including Giovanni Poleni of Italy, Pierre du Buat of France, and John Smeaton of Britain. By contrast, much of the early work on theoretical development of hull forms and ship resistance was performed by people with

Table 3.1

Index of articles on fluid mechanics published 1600–1800

Hydrostatics 125

General 67

Equilibrium 8 (*1 ship theory*)

Measurement 30

Pressure 10

Air 10

Hydrodynamics 668

General 84 (*1 ship theory*)

Air resistance 30

Projectiles 20

Tubes, rivers, canals 26

Percussion 9 (*2 ship theory*)Fluid resistance 32 (*4 ship theory*)Speed of water 11 (*4 ship theory*)

Water jets 6

Hydraulic machines 88

Water mills 94

Pumps and ventilators 112

Hydrotechnics (canals, etc.) 156

Naval Science 239

History 6

Navigation instruments 29 (*2 ship theory*)

Navigation 17

Construction 42 (*24 ship theory*)Rowing 27 (*2 ship theory*)

Launching/hauling 21

Salvage 11

Ship movement 20 (*20 ship theory*)Masts 8 (*4 ship theory*)Admeasurement 4 (*2 ship theory*)

Equipment (capstans, etc.) 23

Ventilation 19

Trim 8 (*6 ship theory*)

Sheathing 4

Total 1032

Total ship-related 251 (24%)

Total with ship theory 71 (7%)

The number of papers related to ship theory is given in italics.

Source: Reuss, *Repertorium Commentationum* (1801–1821/1961), vols. 4 and 7.

no connection to the sea, such as the Bernoullis, Euler, and D'Alembert. Pierre Bouguer and Jorge Juan y Santacilia were somewhat exceptional in this regard.

Ship Theory: Precursors to Newton

Although the term “rational mechanics” was coined by Newton, investigations into fundamental principles began well before him. However, they were hampered by the want of insights and mathematical tools that Newton pioneered, in particular by the lack of an analytic framework for relating hull form to resistance.

Hull Forms

As shown in figure 3.6, European constructors such as Mathew Baker in Britain and P. Chaillée in France used diagrams of fish to explain why the hulls of their ships were shaped with the broadest section forward and tapered aft, commonly cited as “cod’s head and mackerel’s tail.”¹⁴

This explanation did not describe the thought process that constructors went through to create a ship, but was used to justify the shapes that had been employed from the times of their ancestors. This technical justification became so popularized that it found its way into poetry:

By viewing Nature, Nature’s Hand-maid, Art,
Makes mighty things from small beginnings grow;
Thus Fishes first to Shipping did impart,
Their Tail the Rudder, and their Head the Prow.¹⁵

This view was not universally held. Chinese constructors used the model of aquatic birds as justification for their boats, which had the broadest beam aft of amidships, on the grounds that such birds “float between the two media of air and water, while fish swim only in the latter.”¹⁶ This observation was echoed by the English constructor and author William Sutherland in an unpublished manuscript from the 1720s, titled “Action and Reaction,” in which he considered both the mackerel and the duck as shapes to follow, the latter because it is “a Creature that acts in two elements.”¹⁷

Mathematicians occasionally weighed in on the subject of hull form. The British mathematician Thomas Harriot, an acquaintance of Mathew Baker, proposed in an unpublished manuscript (ca. 1610) the use of cubic curves for hull lines and hyperbolic curves for masting. He gave the manuscript to Baker, who apparently never used it.¹⁸ In 1684 the British mathematician John Wallis wrote about the “cono-cuneus,” a blend of conic and circular sections (figure 3.7) based on a wooden model built in 1662 by the naval constructor and Chatham commissioner Peter Pett.¹⁹ Pett in turn

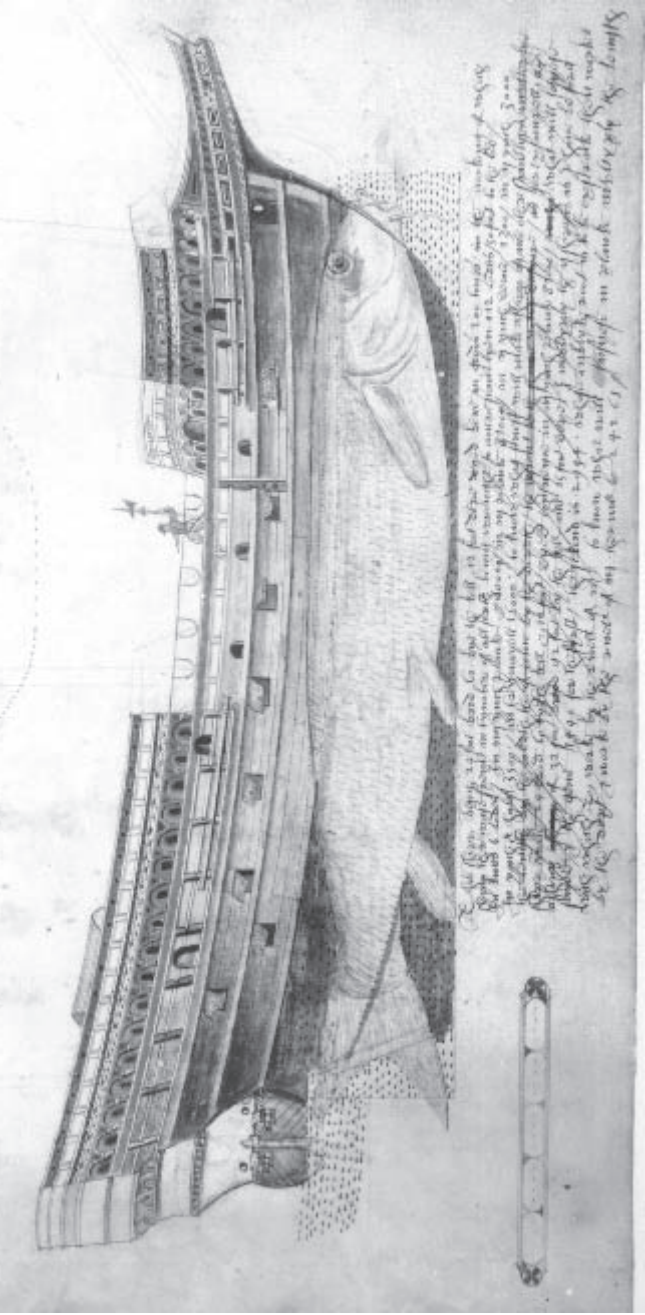
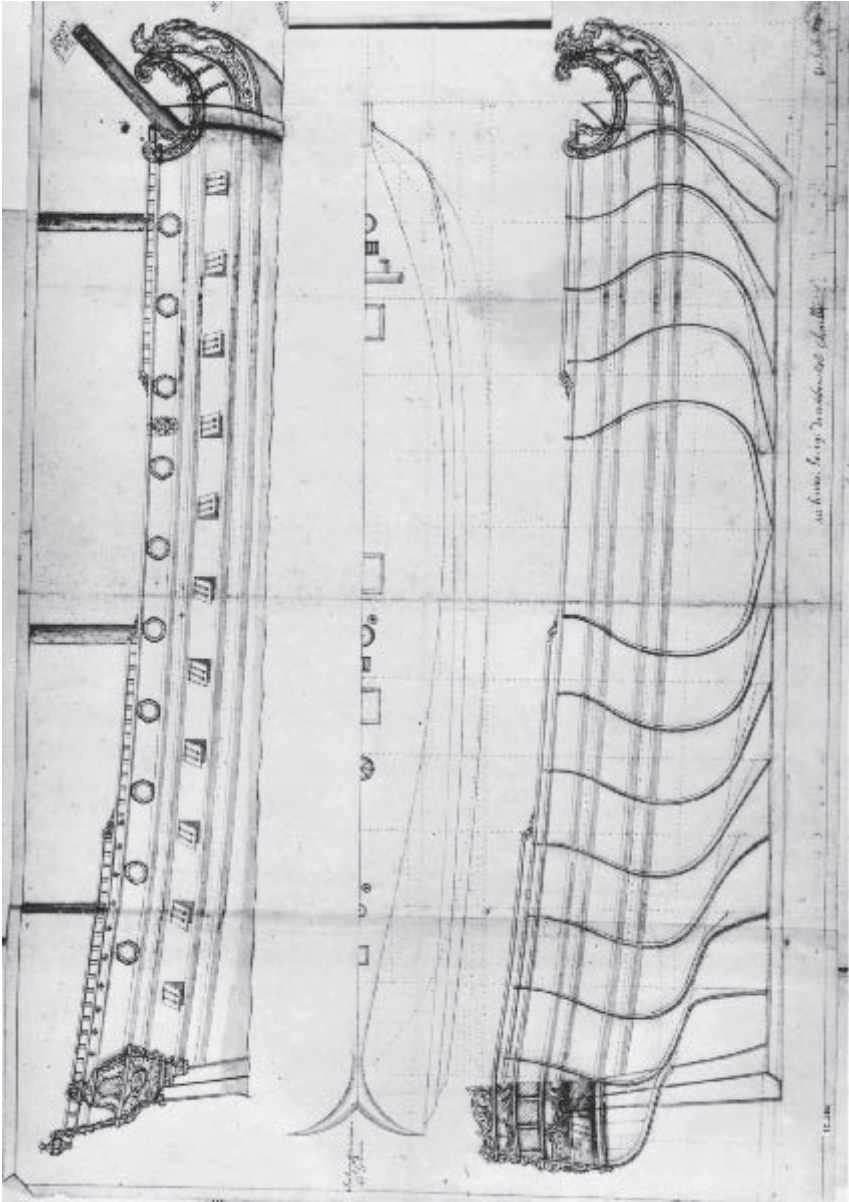


Figure 3.6

Fish and ships. Top: Drawing from "Fragments of Ancient Shipwrightry" by Mathew Baker (ca. 1570). Credit: Pepys Library, Magdalene College, Cambridge. Bottom: Frigate hull with a tuna's tail. P. Chaillée (ca. 1680). Credit: Musée Nationale de la Marine, Paris (photo 11393).



b
Figure 3.6 (continued)

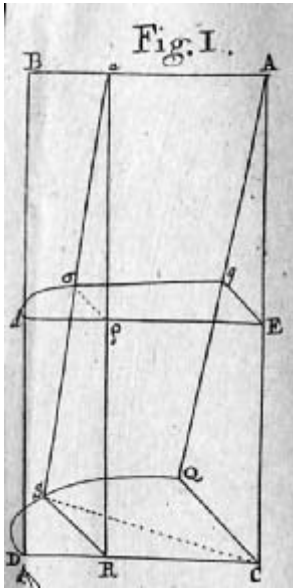


Figure 3.7

John Wallis's cono-cuneus. (Wallis, *Cono-cuneus or the Shipwright's Circular Wedge* [1685], plate 1). Credit: Burndy Library, Cambridge, MA.

may have been inspired by the cone-shaped bow of a catamaran designed by the economist William Petty (as discussed later in this chapter). Wallis himself never justified the advantages of such a shape; for him, it appears to have been more of an exercise in geometry than an attempt to create a fast hull.²⁰

Estimating Resistance

The view that resistance was directly proportional to velocity was held by many early theoreticians, including John Wallis.²¹ The Dutch scientist Christiaan Huygens thought the same, until a series of experiments in 1668–1669 convinced him otherwise. Huygens, along with the French scientist Edmé Mariotte and the astronomers Jean Picard and Giovanni Domenico (Jean-Dominique) Cassini, were asked by the newly formed French Academy of Sciences to confirm the v^2 relationship between height and force originally established in 1640 by the Italian physicist Evangelista Torricelli. The committee set up experiments to measure forces (i.e., equivalent weights) by the use of static balances, and towed wooden blocks in a small tank and attached to a boat moored in the Seine. These towing experiments showed that the velocity of the towed block doubled when the weight quadrupled, thus extending the

v^2 law to force as well as height. The results were not made public until 1698, 30 years after the event and several years after Huygens's death, and even then only in a very short notice rather than a lengthy memoir.²²

Mariotte carried out further studies in 1681 in the newly built reservoir at the château Condé at Chantilly, northwest of Paris, that also confirmed that force on a body is directly related to the area of the body, the density of the fluid, and v^2 . However, he died during an outbreak of plague before he was able to finish his work, so the results were published posthumously in 1686 by fellow Academy member Philippe de La Hire as *Traité du mouvement des eaux* (Treatise on the Movement of Waters), which became one of the most widely used references for hydraulics in the age.²³ Thus, it was Mariotte's, and not Huygens's, experiments that became the basis for later scientists studying fluid shock.

Mariotte appears to have been the first to use the term "shock," previously applied exclusively to the percussion of solids, to describe the action of fluids. His idea (like Huygens's) was to reduce the principles of fluid shock to those of solid percussions, measuring the force of jets of fluid (water and air) by determining how much weight was needed for counterbalance. Mariotte and later scientists would continue to model the force of fluid flow as a hydrostatic phenomenon until 1738, when Daniel Bernoulli showed the difference between the impulse of the dynamic flow and the static condition.²⁴

Although the v^2 laws of Huygens and Mariotte played a key role in the dispute between Renau and Huygens over the *dérive*, as described in chapter 2, the experiments themselves were never used to analyze the effect of hull form on resistance. Likewise, the hull shapes of Mathew Baker and John Wallis had no basis in a theory of resistance. Resistance and hull form were linked for the first time by Isaac Newton.

The Solid of Least Resistance

Newton's *Principia*

Although rational mechanics developed sporadically over many centuries, its coming of age can be dated precisely—26 April 1686, when Isaac Newton deposited his manuscript of *Philosophiae Naturalis Principia Mathematica* (Mathematical Principles of Natural Philosophy) with the Royal Society. It was published at the behest of the royal astronomer, Edmund Halley, in 1687, with two subsequent Latin printings, an English translation in 1729, and a French translation in 1749. The translations did little to make it more understandable, for Newton had developed an entire new vocabulary that took scientists decades to interpret.²⁵

One of the first parts of Newton's work to undergo this interpretation was book II, "The Motion of Bodies in Resisting Media," and in particular section 7, "The Motion of Fluids and the Resistance Encountered by Projectiles."²⁶ Newton visualized fluids as a collection of tiny, hard spheres that created resistance by striking the surface of a moving body and transferring an impulse to the body. In Newton's formulation, all collisions were inelastic, and the instantaneous force transfer was called an "impulsion."

Figure 3.8 illustrates Newton's basic principles of resistance of a body moving through a fluid. As this formed the basis for much of eighteenth-century hydrodynamics, Newton's derivation is worth looking at in some detail.²⁷ He assumed the principle of reciprocity, that is, the resistance of the moving body is identical to the force needed to keep the body standing still in a moving stream. The surface S represents one patch of the overall surface of the body.

As the hard corpuscle m strikes S , it transfers an impulse to the body, which is the difference in momentum before and after the collision. Using the symbols

f = force of individual corpuscle m on an infinitesimal area of surface dS

dF = time-averaged force over a period of time T

n = number of collisions over a period of time T ,

$$\text{Impulse } I = \int_0^T f dt = dFT = nmv \sin \theta.$$

Since the density of the fluid is given by

$$\rho = \frac{n \times m}{dS \times \sin \theta \times v \times T},$$

the equation for the resistance on the infinitesimal area dS is

$$dF = \rho v^2 \sin^2 \theta dS.$$

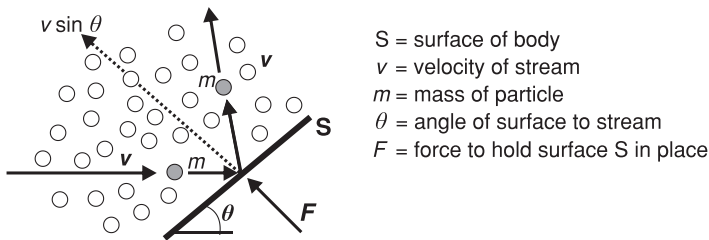


Figure 3.8

Newton's principle of resistance through fluid shock.

In other words, Newton's theorem claimed that resistance was a function of the density of the fluid, the velocity squared, and the square of the sine of the angle of incidence. Integrating over the surface provided the total resistance; for a flat, circular plate of area A , the resistance is

$$\text{Resistance} = \rho v^2 A,$$

which is effectively what Mariotte and Huygens had derived experimentally.

Newton then applied this formula to a sphere, and here the fallacy of the equation can be quickly recognized; integrating it over a closed surface such as a sphere gives a net force of *zero*. Newton therefore integrated it over only the front half of the sphere; in effect his corpuscular theory ignored everything that happened behind the plane S . Thus, the total resistance of a sphere (actually hemisphere) of frontal area A was

$$\text{Resistance} = \frac{1}{2} \rho v^2 A,$$

or half the resistance of a circular plate (or cylinder) of the same frontal area.

The item of interest in this proposition was covered in the scholium,²⁸ where Newton explored the resistance of solids that would generate the least resistance to motion in a uniform fluid. Because this “solid of least resistance” formed the basis of ship hydrodynamics for almost a century, it, too, is worth exploring in some detail.

Newton first used a flat-nosed cone (a frustrum) with a fixed base radius R and height h , and a variable tip radius r (figure 3.9). The problem was to find the radius r of the tip—and thus the angle θ —that would provide the least resistance. This process of finding the minimum value for a given set of parameters—known as the calculus of variations—was poorly understood in 1686, and this example actually predated by a decade the more famous brachistochrone (curve of minimum time of descent) problem. As Newton later explained, the resistance at speed v is

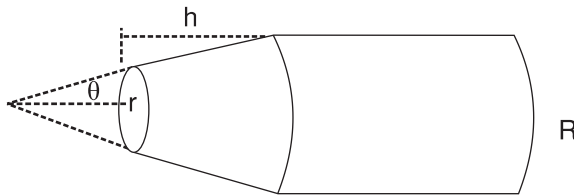


Figure 3.9
Frustrum.

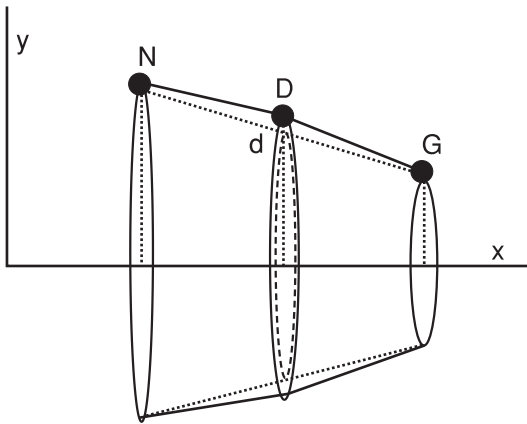


Figure 3.11

Conical frustra for solid of least resistance.

Early Development of the Solid of Least Resistance

The actual text of the scholium was just over one page, and almost devoid of mathematical equations. Newton's explanation of how he derived his solid of least resistance was not published until after his death. As the historian of mathematics Derek Whiteside remarked, "The immediate reaction of Newton's contemporaries to this scholium on its publication in the 1687 *Principia* was one of near-total incomprehension."³² Mathematicians and philosophers who attempted to pursue a practical application of this theory were left with almost no guidance, and no evidence that such a solid was even achievable.³³

Nevertheless, mathematicians were eager to try out Newton's calculus of variations, even though a full account of his methods would not be published until 1704, and the solid of least resistance nicely fit the purpose. A flurry of investigations was carried out over the next two decades, in a back-and-forth exchange of public letters and memoirs that echoed the debate over the *dérive* between Huygens and Renau. The debate over the solid of least resistance, however, was quite personal and became bound up with the priority dispute between Newton and Leibniz over the calculus.³⁴

The first to publish a result was the young French mathematician Abraham de Moivre, then living in Britain. In his 1695 memoir he developed several parabolic and hyperbolic curves that bore little resemblance to Newton's flat-nosed body.³⁵ Newton's longtime friend, the Swiss mathematician Nicolas Fatio de Duillier, was the next to weigh in on the subject, in a 1699 treatise that examined two "minimum" problems, the brachistochrone and the solid of least resistance.³⁶ Fatio's solid was a flat-nosed

parabola that required a fairly long and complex second-order equation for its solution; however, he furnished a table defining the curve in logarithmic form, and pointedly congratulated himself for having discovered an improved form for building ships.

Fatio's memoir probably would have gone unnoticed (as did Moivre's) but for a short paragraph stating that Newton had invented the calculus before Leibniz, and that Leibniz had maliciously appropriated it and then claimed priority.³⁷ This was the first public airing of a dispute that had been simmering in private for some time. Newton did, in fact, invent his system of fluxions (essentially, differential calculus) first, around 1665, but did not publish it for almost 30 years. Leibniz developed his calculus around 1675, and published a short account of it nine years later in the German periodical *Acta Eruditorum* (Transactions of the Learned). From that time until 1699, there was no obvious hint of a dispute; Newton and Leibniz had agreed that each had developed the concepts independently. Fatio's public accusation of plagiarism, in revenge for Leibniz's harsh criticism of his own mathematics a decade earlier, came as somewhat of a bolt from the blue, and he made certain that prominent mathematicians received a copy of his little treatise. Leibniz was of course stung by Fatio's remarks, and enlisted the help of Johann Bernoulli and the editors of the *Acta Eruditorum* in his counterattack on both Fatio's accusation and his mathematical abilities; in effect, any serious investigation into the solid of least resistance was now held hostage by the calculus priority dispute.³⁸

In France, the mathematician Guillaume-François-Antoine, marquis of L'Hôpital, had described an "easy method for finding a round solid" that he claimed followed Newton's solution more closely than Fatio's, which L'Hôpital read at the French Academy of Sciences.³⁹ L'Hôpital was persuaded to also publish this work in *Acta Eruditorum* as a first salvo against Fatio.⁴⁰ Meanwhile, Leibniz published a stinging critique of Fatio's work, followed by a letter from Johann Bernoulli that described a shorter solution to the solid of least resistance that was actually quite similar to L'Hôpital's approach.⁴¹ Within a few months, Leibniz wrote a longer rebuttal to Fatio's accusations over priority, which Bernoulli followed with a more developed memoir on the solid.⁴² Fatio responded in a published letter to his brother Jean-Christophe Fatio with an ingenious second-order solution using Pierre Fermat's law of diffraction (the path that takes the shortest time for a light ray to follow).⁴³ Meanwhile, the English mathematician John Craig published his own solution, though he tactfully kept Fatio's name out of the discussion.⁴⁴ Through all this, Newton kept silent, content to let others wage his battle. Finally, Fatio revisited the problem 13 years later (soon after a Royal Society commission "awarded" priority to Newton), arriving at a solution similar to that obtained by L'Hôpital and Bernoulli.⁴⁵

Original analysis of the solid of least resistance effectively stopped after 1714, with the solutions of L'Hôpital and Bernoulli generally favored by mathematicians teaching maximum/minimum problems in their textbooks.⁴⁶ In 1745, the young French astronomer Guillaume de Saint-Jacques de Silvabelle, who had recently discovered Newton for himself, set about resolving several problems posed in the *Principia*, and developed what he considered an entirely new approach to Newton's solid.⁴⁷ This was the last effort to develop a purely mathematical application to the solid of least resistance.

The Solid of Least Resistance in Ship Theory

The application of infinitesimals to rational fluid mechanics remained unattainable to all but the most skilled mathematicians, until a series of interpretations by authors such as Varignon, Jacob Hermann, and Johann Bernoulli began appearing in the late 1600s.⁴⁸ Many of Newton's concepts were received only secondhand; for example, the British constructor William Sutherland mentioned the solid of least resistance as a "blunt and flat-headed" shape without providing any details, and later suggested that a ship's body could be modeled on the solid but with the axis following a curved construction line instead of being straight.⁴⁹

An example of secondhand knowledge of Newton gone awry is the interpretation of resistance by Paul Hoste in his 1697 synthesis of naval architecture, *Théorie de la construction des vaisseaux* (Theory of the Construction of Vessels). Hoste never mentioned the solid of least resistance, but he demonstrated that he had at least heard of Newton's theories when he stated that fluid resistance was due to the shock of particles in "an infinitely small time." However, he immediately ignored the rest of Newton by presuming that the resistance of a body was equal to the mass of the water it displaces and its speed; in figure 3.12, the resistance of the body D is equal to the path $A \rightarrow B$ without the intermediate path C, because the lateral movement $A \rightarrow C$ is equal to $C \rightarrow B$. Hoste then argued that because resistance was proportional to the mass and speed of the fluid displaced, shapes with the smallest perimeter (e.g., globes) had the least resistance.⁵⁰ Although his analysis was wrong even by the standards of the day (the v^2 proportionality of resistance was by then known in France through Mariotte's work), to Hoste's credit he had at least defined a clear theoretical basis for choosing one hull form over another, although he never gave any supporting equations for constructors to use during design. By contrast, Renau's elliptical theories had never provided any such basis for comparison.

The theoretical connection between the solid of least resistance and hull shapes was first made by the French mathematician Charles René Reyneau in his 1708 textbook

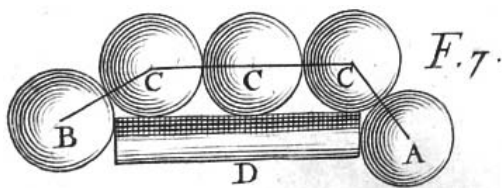


Figure 3.12

Hoste's interpretation of fluid resistance. (Hoste, *Théorie de la construction des vaisseaux* [1697], chapter 2, plate 1). Credit: U.S. Navy Historical Center.

Analyse démontrée (Analysis Demonstrated), one of the first on the Continent to explain the newly invented calculus. Reyneau used calculus to solve practical problems; the solid of least resistance was pointedly titled “Find the curved figure given to the bow of a vessel so that it moves in the ocean with the greatest possible speed, or so that it meets the least resistance possible in seawater.”⁵¹ Although the flat-nosed solid was derived from the recent work of L'Hôpital and Bernoulli, Reyneau included a slight modification to allow for the construction of a “pointed bow,” perhaps realizing that a flat bow would be almost impossible to build.

The practical possibilities of this “bow of least resistance” were worked out some twenty years later by Pierre Bouguer. In his 1727 prize entry “De la Mâtüre des vaisseaux” (On the Masting of Vessels), Bouguer provided a method of calculating the shock of water on the bow by dividing the bow into panels (described later in this chapter).⁵² He also briefly noted that Reyneau had developed the mathematical equations for a “most advantageous bow” and provided a table of offsets on how to form it.⁵³ But Reyneau's bow had a semicircular base, and Bouguer of course realized this was an artificial constraint for a real ship's bow; another limitation was that the “solid of least resistance” assumed a flow parallel to the axis, whereas real ships often sailed at an angle of *dérive*. In 1733 he published a memoir explaining how to develop a bow of least resistance having any parabolic base and any predetermined length.⁵⁴ Besides providing a broader scope for the physical constraints, the equations for the bow (figure 3.13) were developed so that it would produce the least resistance over a wide range of leeway angles. The base ABC is any parabola, and the length DE is predetermined; Bouguer's equations developed the curve CE and subsequent surfaces to provide the least resistance. Bouguer also contended that the same bow would produce the least *dérive*, so that the ship would retain the straightest possible course.

This memoir was the last that Bouguer published on ship theory before he left for Peru, although he continued to carry out experimental research on “the shock of

where the integration was performed over the front surface. Now, in modern terms, resistance R can be expressed with the formula

$$R = \frac{1}{2} \rho v^2 C_d S,$$

where C_d is the nondimensional drag coefficient of a body, usually obtained by experiment. To equate Newton's formulation (i.e., without the term $1/2$) with the modern formula, the C_d for a flat plate perpendicular to a stream should be exactly 2.0. In fact, it is around 1.16 (depending on several factors). Bouguer's practical experiments on the "shock of fluids," measuring the force on a 1-*pie*-square block of wood in a stream, gave him an equivalent $C_d = 1.21$ (later amended to 1.0) for a flat plate—close to the modern value but quite different from that proposed by Newton. Bouguer stated this unusual result without comment. Euler, on the other hand, at first postulated a C_d of either 2.0 (if using conservation of momentum) or 1.0 (using conservation of *vis viva*), but eventually settled on 1.0 by noting that this coincided more closely with experimental results, in spite of the fact that it contradicted Newton.⁵⁹ In essence, Euler had added the term $1/2$ to the *vis viva* equation almost a century before Gustave Gaspard Coriolis did the same to develop the modern version of kinetic energy (as will be described later in this chapter).

Calculating Resistance for Plane Figures and Curved Bows Both Bouguer and Euler began their resistance investigations with two-dimensional figures (triangles, semicircles, and parabolas), both along their axes and on oblique routes, followed by calculations for curved surfaces. Euler gave results for a variety of mathematical shapes, including prisms, cones, lenticular forms, and ellipsoids (including Wallis's conocuneus, which he found inferior to other bodies).⁶⁰ Bouguer developed only a generalized formula for a cone-shaped bow.⁶¹ Rather, he explained how to derive results using the actual plan of the hull, which became the basis for the hydrodynamic calculations used by French constructors.

As he initially described in his 1727 "De la Mâtire des vaisseaux," Bouguer's first step was to divide the curved surface into flat panels and measure the angle of incidence of each panel (as shown later, in figure 3.15). Multiplying the area of each panel by the sine squared of the horizontal angle of incidence gave the "impulsion" (a confusing term that meant both drag and thrust); summing the panels gave the total impulsion.⁶² Bouguer also extended the explanation to determine impulsion on oblique routes.

It is quickly obvious that in the above formulation, "impulsion" was simply an area, not the actual force of resistance in *livres*.⁶³ Even when correlating ship speed with

wind speed, Bouguer did not actually calculate resistance by using the results of his shock-of-fluids experiments, but instead used the densities of water and air to arrive at “relative impulsions,” calculating that a 74-gun ship would travel between 23 percent and 29 percent of the wind speed.⁶⁴ Another “relative impulsion” referred to the comparison of the resistance of the bow shape with that of a flat plate equal to the midship section; it was this “relative impulsion” that became the crux of the hydrodynamic calculations that would be used by French constructors.

Bows of Least Resistance Euler developed equations for each of the bow types studied—ellipsoid, lenticular, and others—that offered the least resistance, as opposed to providing a single “best” bow form. The equations were, however, extremely complex, in one case requiring the solution to an infinite series.⁶⁵ Bouguer made a point of distinguishing between two bow types: least resistance and greatest speed. He developed families of “bows of least resistance,” based on different shapes (e.g., triangles, cones, etc.), and in each case “saved the Reader the effort of calculation” by inserting tables of offsets to construct the curves.⁶⁶ His “bows of greatest speed” were generally similar to those of least resistance, but with the *point vélique* (see chapter 2) taken into account so that they were generally fuller, in order to move the *point vélique* higher so the ship could carry more sail.⁶⁷

Impulsion of the Stern Bouguer, unlike Euler, attempted to take into account the effect of the stern of the ship, which had been neglected by Newton and subsequent theorists in their calculation of resistance, and which would not be looked at in further detail until D’Alembert’s investigations in 1752. Bouguer’s idea was that the advancing ship leaves a void behind it (figure 3.14) that the incoming water (with velocity

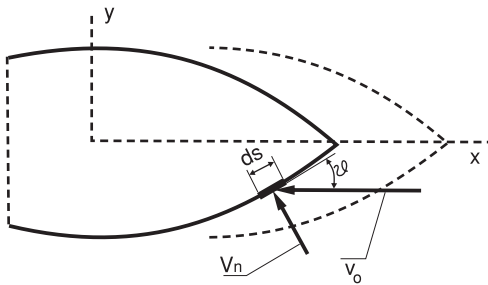


Figure 3.14

Bouguer’s assumption of the impulsion of the stern. (After Simón Calero, *La génesis de la mecánica de los fluidos* [1996], p. 215)

v_a) must fill. The resulting normal force v_n pushes the ship forward; by this example, a flat stern would offer no forward thrust. In this theory, there was a “stern of greatest impulsion” that Bouguer defined by equation and with a table of offsets. Marrying this stern to a bow of least resistance would, in Bouguer’s theory, create the fastest ship possible.⁶⁸

It was comparatively easy for mathematicians to develop these theories, equations, and curves for the fastest ship forms. It was quite another task for constructors to build hulls with these shapes, given the enormous practical difficulties in hewing, forming, and laying up and piecing together the enormous timbers that, in reality, dictated the rounded curves of the bow and the sweep of the lines.

Were Any Ships Built to a Form of Least Resistance?

Although no proof has come down to us in the form of, say, plans or models showing a hull built as a solid of least resistance or with a bow of least resistance, there have been several enigmatic accounts alluding to this practice. Most of them are quite believable in that they probably interpret the *intent* of the designers to follow “scientific” principles, but without actual plans or models it is impossible to assess how far they went in applying them.

Probably the most famous account of a “scientifically” designed ship appeared before Newton’s *Principia*. According to a brief account in 1717, the 84-gun *Royal Katherine*, built in 1664 by Christopher Pett, “was contrived by the Royal Society, and yet was Girdled.”⁶⁹ Later historians used the account as a screed on the failure of science in shipbuilding.⁷⁰ As the technology historian David McGee notes, there is no corroborating account of this in the records of the Royal Society.⁷¹ However, the circumstantial evidence of timing and key figures points to the possibility of the cono-cuneus as the “scientific” principle. As stated earlier, Peter Pett may have been inspired to come up with the wedge-cone at the January 1662 Royal Society meeting, at which William Petty, who built the catamaran *Double Bottom* (or *Experiment*) with a cone-shaped bow, argued that the bow would drive through waves better than standard forms.⁷² Pett then inspired John Wallis to develop the cono-cuneus in April 1662. Wallis, Petty, and Peter Pett were all members of the Royal Society, and Christopher Pett was Peter’s younger brother. The inference here is that two years later, Christopher Pett worked with his brother, Wallis, and Petty to adapt the cono-cuneus for the lines of *Royal Katherine*. The fact that it was “girdled” (i.e., widened) points to a problem of stability, not uncommon at the time but also (possibly) a result of the novel hull form.

The next account appeared after Newton’s solid of least resistance became known in France through L’Hôpital’s 1699 memoir. This new theory caught the attention

of the Lorient constructor Gobert (his first name is not recorded), who in 1705 claimed to have incorporated L'Hôpital's solid of least resistance for the hull lines of the 74-gun *Saint Michel*.⁷³ However, Gobert's claim must be treated with considerable skepticism; L'Hôpital's solid ended in a Newtonian flat nose, so the actual hull lines would have had to be much different to terminate in the rounded bow of a ship.

Two espionage missions by French naval constructors in Britain during the 1730s yielded tantalizing clues to a widespread investigation and use of Newton's solid in naval shipbuilding, although (to my knowledge) there are no contemporary British accounts to corroborate this. From 1729 to 1732, Blaise Geslain visited several British dockyards under the orders of Minister of the Navy Maurepas. In his short report, he claims to have brought back plans of several vessels, including "a frigate of 20 Guns of new Construction on the precepts of the Cone demonstrated and explained by the scholar [Isaac Newton]."⁷⁴ In 1737, Maurepas sent Blaise Ollivier to Britain and Holland, from which he returned to write a very lengthy account of ship design and building practices. Of ships designed to Newton's solid, he said:

The English claim . . . that they have given to their new ships the shape of the solid of least resistance proposed by Mr. Newton, and it is on this in particular that they found their hopes that the new ships will be faster sailers than the old. . . . Such a solid cannot on its own form the shape of the bow, or else the ship would roll excessively. . . . It can therefore be employed only to form part of the bow. . . .

The English Master Shipwrights discovered these difficulties when they sought to employ the solid of least resistance, and believe they have overcome them, by diverse experiments which they have carried out in the dock at Deptford, where they floated and drew through the water pieces of wood of different shapes.⁷⁵

Ollivier went on to explain that he found the "solid of least resistance" models to have the midship bend (area of greatest cross section) much farther forward than conventional models, and that the ships were made even faster by increasing masts, spars, and sails. He claimed that the 44-gun *Eltham*, built at Deptford in 1736, was built to this new design, but that it was unseaworthy and had to be reballasted.⁷⁶ This account is to some extent supported by a letter from the Prussian king Friedrich II to Voltaire, dated January 1778, stating, "The English have built ships with the most advantageous section in Newton's opinion, but their admirals have assured me that these ships did not sail nearly so well as those built according to the rules of experience."⁷⁷ A similar account was repeated in John Charnock's *History of Marine Architecture*, claiming that in 1779 a 38-gun frigate was constructed "according to a form which the most attentive and experienced theoretical opinions considered as

likely to be conducive to velocity and stability”; but which did not perform well until its forward guns were run all the way aft to trim it by the stern, after which it sailed normally.⁷⁸

Finally, it should be noted that in 1777, the Italian constructor Odorico Panfilli, in charge of the Compagnia Orientale (East Indies Company) dockyard at San Nicolò near Trieste, claimed to have used Bouguer’s method to design a bow of least resistance, but no further details are given.⁷⁹

Here, then, are some naval architecture mysteries that remain to be investigated, although the lack of plans has so far proved to be an insurmountable obstacle. Was there an extended effort, especially in Britain, to build ships to the solid of least resistance? Which ships and constructors? What were the results of the experiments at Deptford? To what extent was the solid of least resistance used in the design, what did the hull lines look like, and how successful were they considered at the time?

The Ratio of Bow Resistance in Ship Theory

Despite the exertions of Bouguer and Euler to define bows of least resistance for use by constructors, the only part of the extensive evolution of shock theory and the solid of least resistance that found its way into systematic practice was a few pages of *Traité du navire* that described the “relative impulsion” of the bow.⁸⁰ This transition from theoretical hydrodynamics to practical ship design was entirely due to the inspector general of the French navy, Henri-Louis Duhamel du Monceau, who was also in charge of the School of Engineer-Constructors of the Navy (described in chapter 6). One of Duhamel du Monceau’s tasks was to develop the curriculum for the students, for which he wrote a practical guide to ship construction, published as *Éléments de l’architecture navale* (Elements of Naval Architecture) in 1752.

Duhamel du Monceau’s great achievement in *Éléments* was to render the complex mathematics of Bouguer in a simple, systematic format that students could use by rote. His synopsis of the “shock of fluids” theory was completely devoid of equations, explaining the concept in general terms instead.⁸¹ For the “relative impulsion” calculations, he wisely changed the name to the more straightforward “ratio of bow resistance,” and provided tables that codified the hydrodynamic calculations. Duhamel’s book was used from the start by both students and working-level constructors; it is therefore instructive to examine both his textbook and letters from his former students, explaining how the ratio of bow resistance was calculated. One constructor repeated back, almost word for word from Duhamel’s book, the process of calculating each hull panel:

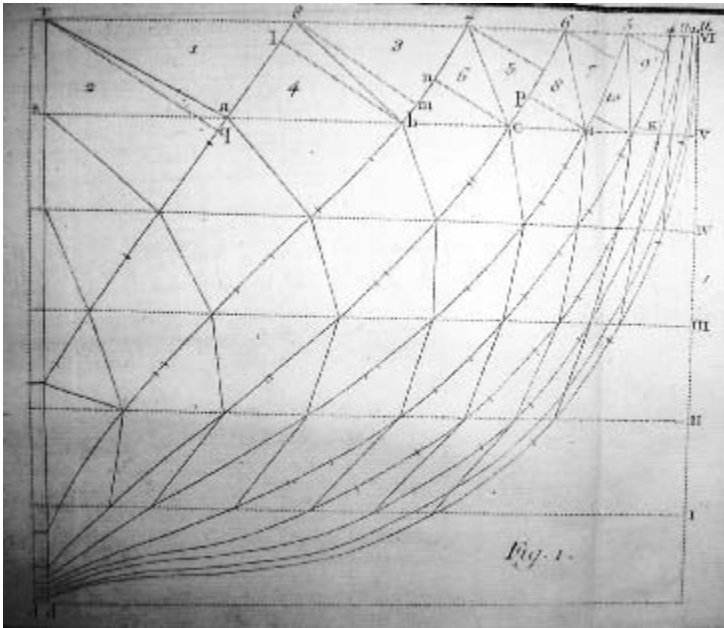


Figure 3.15

Division of bow into planar elements in order to calculate ratio of bow resistance. Note the resemblance to modern finite-element studies. (Duhamel du Monceau, *Elémens de l'architecture navale* [1752], p. 392) Credit: U.S. Navy Historical Center.

After having divided the whole of the bow into flat Triangles of horizontal and oblique section [see figure 3.15], the next step is to multiply the face of each projected triangle by the square of the sine of the angle of incidence of the fluid on the corresponding triangle, and this product gives the Impulsion of the triangle. Making a sum of all the impulsions [see figure 3.16] one will have the total impulsion. To measure the triangles with ease, each triangle must be bounded between two waterlines and have a common height, so one is not obliged to separately measure each one.⁸²

In the calculations partially shown in figure 3.16, the bow was divided into six waterlines of 14 triangles each. The area of each triangle was reduced by the sine squared of the angle of incidence, to obtain the equivalent projected area exposed to fluid shock. The sum of the equivalent areas, 374.26 *pieds* square, was divided into the area of the midship section, 3,304.7 *pieds* square, to obtain a ratio of the resistance of the bow to the midship section of 1:8.8. This ratio was indicated on plans as the “ratio of bow resistance.”

Calcul de la Résistance d'un Vaisseau de 74 canons.

1^{re} tranche (Waterline)

2^e tranche

3^e tranche

Triangle	Hauteur	1/2 base	Surface	Sine carré	Effort	Triangle	Hauteur	1/2 base	Surface	Sine carré	Effort	Triangle	Hauteur	1/2 base	Surface	Sine carré	Effort
1	8.2	2.2	18.04	4.0	72.21	3	2.5	12.34	2.6	31.68	2.6	2.1	7.36	1.5	9.82		
2	8.0	1.7	13.60	3.9	53.04	4	1.6	7.84	2.0	15.68	2.1	1.3	5.57	0.6	2.14		
3	4.6	1.9	8.74	1.8	15.73	5	2.2	9.90	1.7	16.83	3.4	2.6	9.88	1.1	13.83		
4	4.6	2.2	10.12	1.8	19.72	6	2.5	10.12	1.6	16.19	3.7	2.1	7.77	1.5	10.09		
5	2.6	1.8	4.68	0.7	2.23	7	2.1	5.88	0.8	4.70	2.8	2.4	6.72	0.8	5.57		
6	2.8	1.9	5.32	0.8	4.34	8	2.8	6.16	0.8	4.92	2.8	2.6	7.28	0.8	5.82		
7	1.5	1.7	2.21	0.2	0.44	9	1.9	2.85	0.5	0.86	1.8	2.1	5.78	0.5	1.89		
8	1.4	1.8	2.52	0.2	0.78	10	2.1	3.57	0.4	1.42	1.9	2.4	4.56	0.5	2.28		
9	0.7	1.7	1.19	0.1	0.11	11	1.8	1.66	0.1	0.14	1.2	1.9	2.28	0.2	0.45		
10	0.8	1.7	1.56	0.1	0.15	12	1.9	2.09	0.2	0.20	1.5	2.1	2.15	0.5	0.64		
11	0.5	1.7	0.51	0.1	0.08	13	1.7	0.68	0.1	0.06	0.6	1.9	1.14	0.1	0.11		
12	0.4	1.7	0.68	0.1	0.06	14	1.7	1.02	0.1	0.10	0.7	1.8	1.16	0.1	0.11		
13	0.2	1.7	0.34	0.1	0.03	15	1.7	0.54	0.1	0.05	0.4	1.8	0.72	0.1	0.07		
14	0.5	1.7	0.51	0.1	0.08	16	1.7	0.68	0.1	0.06	0.5	1.8	0.90	0.1	0.09		

169.33

95.88

32.71

a

A partial translation, to highlight the process:

1st waterline slice

Second slice

Triangle	Height	1/2 base	Area	Sine squared	Effort	Height	1/2 base	Area	Sine squared	Effort
1	8.20	2.20	18.04	4.00	72.21	5.80	2.30	13.34	2.60	34.68
2	8.00	1.70	13.60	3.90	53.04	4.90	1.60	7.84	2.00	15.68
3	4.60	1.90	8.74	1.80	15.73	4.50	2.20	9.90	1.70	16.83
:	:	:	:	:	:	:	:	:	:	:
14	0.30	1.70	0.51	0.10	0.05	0.40	1.70	0.68	0.10	0.06

b

169.33

95.88

Figure 3.16

Tabulation and calculation of bow resistance for a 74-gun ship. (Segondat-Duvernet, "Calcul de la résistance d'un vaisseau de 74 canons" [1766]). Top: Original table. Bottom: Partial translation. Credit: Phillips Library, Peabody-Essex Museum.

This coefficient by itself did not provide any meaningful indication of the performance of a ship, but a comparison with existing ships did. Duhamel provided examples for such a comparison, and related them to their sailing performance. In rough terms, the higher the coefficient, the faster the ship. For example, the 56-gun *Brillant*, by all accounts a slow sailer, had a ratio of bow resistance of 1:3.5, while the 26-gun *Renommée*, with a coefficient of 1:10, was considered a very fast ship.⁸³ In practice, however, many ships with a low ratio were considered faster than ships with a high ratio, and vice versa.

No other navy required the calculation of the ratio of bow resistance, and this was taken by many observers (both inside and outside France) as evidence of the superiority of the French navy in using theoretical hydrodynamics to design fast ships. As will be shown later, this was an inaccurate conclusion at best; the speed of a sailing ship in that era depended less on the hull form and far more on factors such as the sail plan and material, the condition of the hull (clean or barnacle-encrusted), and, most important, the skill of the commanding officer and his crew.

Nonetheless, the ratio of bow resistance was the only tool available to French constructors to assess performance, and their superiors ensured that they made full use of it. As discussed in chapter 6, the ordinance of 1765, under Minister of the Navy Choiseul, formalized the data that had to be indicated on ship plans, which included calculations for the “center of resistance” (which, though not obvious, meant “ratio of bow resistance” in practice). Constructors spent long hours and days in this arduous number-crunching, often performed to the hundredth decimal place despite the ubiquitous arithmetical errors that made the sums wrong anyway.

In 1773, Leonhard Euler published an abridged version of *Scientia Navalis*, titled *Théorie complète [sic] de la construction et de la manoeuvre des vaisseaux* (Complete Theory of the Construction and Maneuvering of Vessels), that was aimed squarely at naval constructors. One of his concessions to the practical needs of constructors was to depart from his usual elegant analyses of fluid mechanics, in order to provide a simplified method of calculating the ratio of bow resistance based solely on L/B (i.e., the ratio of length to beam).⁸⁴ Euler argued (correctly) that existing methods required great effort for quite unreliable results, although his own simpler method was equally unsatisfactory, since most ships fell within a very narrow range of L/B (around 3.0 to 4.0), so his method could not adequately differentiate between them. Yet it is not clear why Euler had provided constructors this simple method in the first place; by 1773, he already knew that the underlying principles of fluid shock were wrong, because he was central to creating the theories that imparted the first shock to Newton’s increasingly fragile edifice.

Evolution of Hydrodynamic Theory

The attack on Newton's edifice took place on two allied fronts, theoretical and experimental. Under this assault, shock theory, based on the impact of fluid particles against a solid body, gradually gave way to streamlines, pressure, and general equations of movement. In general, the people at the forefront of theoretical developments did not carry out experiments, and vice versa. Nonetheless, the work done in the one area informed and confirmed the results of the other.

The “grand theorization” of hydrodynamics was carried out by just five mathematicians: Daniel and Johann Bernoulli, Jean Le Rond D'Alembert, Alexis-Claude Clairaut, and (most important) Leonhard Euler. Figure 3.17 represents how that the-

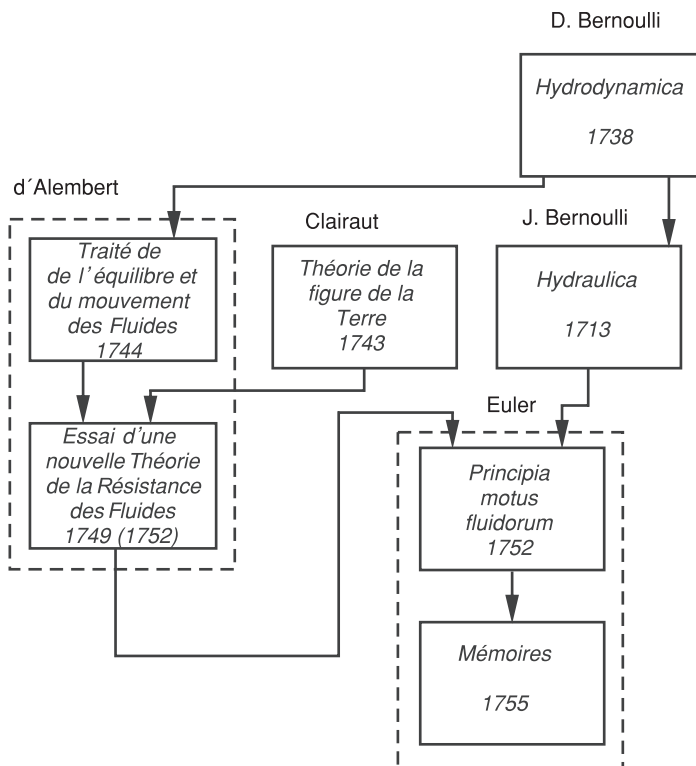


Figure 3.17

The “grand theorization” of hydrodynamics, as proposed by Julián Simón Calero. (After Simón Calero, *La génesis de la mecánica de los fluidos* [1996], p. 493)

orization occurred. It is no exaggeration to say that the works of the first four laid the groundwork of hydrodynamics for Euler's magisterial synthesis of the subject.

The first great work on hydrodynamics actually gave the discipline its name. Daniel Bernoulli began writing *Hydrodynamica, sive de Viribus et Motibus Fluidorum Comentarii* (Hydrodynamics, or Commentaries on Forces and Motions of Fluids) around 1729, while he was still a professor of mathematics at the Saint Petersburg Academy of Science, but it was not published until 1738. He coined the term "hydrodynamics" to mean the study of both the static equilibrium of fluids and their movement. In fact, *Hydrodynamica* was devoted almost exclusively to what we would today term hydraulics, generally denoting the theory of internal flow of liquids (e.g., through pipes, channels, and orifices), and had almost no relationship to the modern concept of ship hydrodynamics.⁸⁵

Daniel Bernoulli introduced several novel concepts, including, for the first time, a differentiation between the impulse of dynamic flow and the static condition. *Hydrodynamica* was, however, most famous for an equation that it never contained. The now famous "Bernoulli equation" that relates pressure and velocity, $P + 1/2\rho v^2 = \text{constant}$, was first stated explicitly by the French scientist Gustave Gaspard Coriolis in 1829. The original equation looked nothing like that. Daniel Bernoulli first investigated fluid pressure and velocity in terms of the conservation of *vis viva* in his 1727 treatise related to blood pressure, echoing his original medical training.⁸⁶ In *Hydrodynamica*, the relevant problem was to measure the pressure in a pipe connected to a reservoir of water of height h . He showed that pressure in the pipe (which he stated as $v dv/dx$) was proportional to the height of a spout of water ejected from the pipe (z) and the ratio of diameters of the pipe and spout (c). Bernoulli's original equation was thus

$$z = h \frac{c^2 - 1}{c^2}.$$

Although this does not resemble the modern Bernoulli equation (several substitutions, such as $P = \rho gz$, would give that result), this was the first expression of pressure as a function of velocity and acceleration.⁸⁷

But Daniel Bernoulli did not yet have the important concept of internal pressure of fluids. This insight was soon developed by his father, Johann Bernoulli, in "Hydraulica."⁸⁸ Where Daniel expressed pressure as acting only on the walls of the pipe, Johann described the pressure as acting everywhere within the fluid. In particular, Johann developed the outlines of the modern "Bernoulli equation," describing the pressure at reference a_1 along a tube of varying cross section (A_0, A_1) and velocity

(V_0 , V_1) by means of dynamic rather than static principles, here expressed in modern terms:

$$\rho gh = \frac{1}{2} \rho A_0 (V_1^2 - V_0^2) + \rho A_0 A_1 a_1 \int \frac{dx}{A}$$

potential energy kinematic energy unsteady acceleration

The separate works of Daniel and Johann Bernoulli, though generally considered as an ensemble, would affect the development of hydrodynamics in different ways.⁸⁹

“Hydraulica” was first published as a part of Johann Bernoulli’s complete works in 1742. The following year saw the publication of Alexis-Claude Clairaut’s *Théorie de la figure de la terre* (Theory of the Shape of the Earth), which was a natural outgrowth of his participation in the Geodesic Mission to Lapland under Maupertuis.⁹⁰ Bouguer had previously studied the Earth’s shape as a rotating mass of fluid in equilibrium, which had earned him a place on the Geodesic Mission to Peru.⁹¹ But where Bouguer’s model assumed the Earth to be a homogeneous (single-density) fluid, Clairaut’s insight was to envision a multilayered Earth, each layer having a different density, with the total sum of forces through these layers being zero as a requirement for equilibrium.⁹²

This fundamental principle of equilibrium was stated mathematically in terms of a vector field with a gradient, allowing the forces to be accounted for in “layers.” If the overall force on a fluid element is decomposed into its x , y , and z values, then the sum of the effort $F_x dx + F_y dy + F_z dz$ is a complete differential, so that the governing condition for equilibrium is that the F_x , F_y , and F_z gradients are equal when measured orthogonally, as expressed by the partial differentials

$$\frac{\partial F_x}{\partial y} = \frac{\partial F_y}{\partial x} \quad \frac{\partial F_x}{\partial z} = \frac{\partial F_z}{\partial x} \quad \frac{\partial F_y}{\partial z} = \frac{\partial F_z}{\partial y}.$$

One of the results of this equilibrium condition is that the free surface (i.e., the level at which the surface of the fluid reposes) is necessarily a constant distance from a central force, a result known (but not rigorously described) since Archimedes.⁹³

The problem of fluid equilibrium was also explored by Jean Le Rond D’Alembert in his 1744 *Traité de l’équilibre et du mouvement des fluides* (Treatise on the Equilibrium and Movement of Fluids).⁹⁴ This treatise employed the principle he had previously developed to model dynamic forces as equivalent static loads.⁹⁵ He used this principle to reexamine Daniel Bernoulli’s application of *vis viva* to fluid flow, arriving at much the same results, as well as Clairaut’s equilibrium condition for “layers” of fluids.

Although *Traité de l’équilibre* essentially reproduced other scientists’ results using different methods, it helped inform D’Alembert’s next work, *Essai d’une nouvelle théorie*

de la résistance des fluides (Essay on a New Theory of the Resistance of Fluids).⁹⁶ The treatise was originally submitted to the Berlin Academy of Sciences in 1749 as an entry in its prize competition on the resistance of fluids. With Euler as president of the Academy and head of the prize committee, the standards were too high for the entrants; all manuscripts were returned with the admonishment to compare their predictions with experimental results. D'Alembert, famously unwilling to sully his hands with experiments or even to perform basic arithmetic, promptly withdrew and had his treatise published several years later.⁹⁷

The *Essai d'une nouvelle théorie* is best known for introducing the "D'Alembert paradox," which is nowadays glossed over in every introductory course on hydrodynamics: in a perfect fluid (i.e., no friction) the resistance of a body is theoretically zero because the pressure field on the forward side is the same as that on the rearward side (figure 3.18). This simple statement obscures two critical concepts that D'Alembert first broached, if not very successfully: first, that resistance was due to *pressure* (not impact), and second, describing dynamics in terms of a *field*. D'Alembert arrived at these theories by using the equilibrium condition he previously developed for parallel "layers" of fluid, as well as borrowing from (without crediting) Clairaut's partial differential equations.

Essai d'une nouvelle théorie marked a distinct break from D'Alembert's previous work, and indeed from the work of his contemporaries. Only a few years before, in *Traité de*

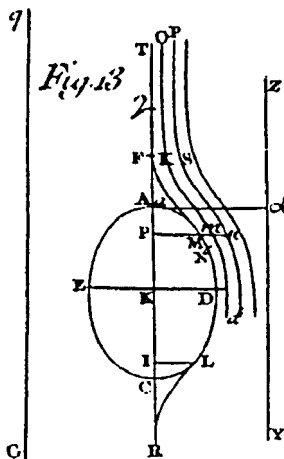


Figure 3.18

D'Alembert's paradox. (D'Alembert, *Essai d'une nouvelle théorie de la résistance des fluides* [1752], plate 1). Credit: Bibliothèque Nationale de France/Gallica.

l'équilibre, he had modeled resistance as a series of impacts of fluid particles, just as Newton had done 60 years earlier. In *Essai d'une nouvelle théorie*, those same fluid particles no longer impacted the body but flowed around it, transmitting resistance primarily through the pressure exerted by their acceleration as they continually changed direction around the body.⁹⁸

D'Alembert's *Essai d'une nouvelle théorie* was a success in that it was widely read and cited by his contemporaries, even though it was dense, imprecise, and very difficult to follow. This success was short-lived, however, for within three years Leonhard Euler would elegantly sum up the work of D'Alembert and his predecessors in three memoirs that would form the cornerstone of hydrodynamics. The memoirs were in the same volume (1755) of the *Histoire de l'Académie Royale des Sciences et des Belles-lettres de Berlin* (History of the Royal Academy of Science and Literature of Berlin), published by the Berlin Academy, where Euler was then working:

- "Principes généraux de l'état de l'équilibre des fluides" (General Principles of the State of Equilibrium of Fluids)
- "Principes généraux du mouvement des fluides" (General Principles of Movement of Fluids)
- "Continuation des recherches sur la théorie du mouvement des fluides" (Continuation of Research on the Theory of Movement of Fluids).

In fact, Euler had first explained the principles in a previous memoir, "Principia Motus Fluidorum" (Principles of the Motion of Fluids),⁹⁹ read before the Berlin Academy in 1752. That work was published by the Saint Petersburg Academy, subsequent to the three memoirs, and was in Latin (thus not very accessible); therefore most scientists and mathematicians learned the new principles of hydrodynamics through Euler's Berlin memoirs. In the words of the historian of rational mechanics Clifford Truesdell, "The paper we are discussing is a turning point in the history of physics. . . . The main specific contribution . . . is the full elaboration of the concept of pressure and its applications."¹⁰⁰

Newton's model of fluids was a collection of hard particles imparting resistance through inelastic collisions; there was no satisfactory mathematical treatment of a fluid as a deformable mass. The first step in this treatment was Daniel Bernoulli's linkage of fluid pressure with its velocity, and Johann Bernoulli's crucial insight into the concept of internal pressure by modeling the fluid as composed of infinitesimal elements. Clairaut expressed equilibrium through partial differentials, and D'Alembert introduced the concept of resistance due to pressure, not impact. These analyses all advanced the level of knowledge immensely, but Euler was able to synthesize them

into a few clear statements that would serve as the fundamental equations for hydrodynamics. Euler was well aware of what he had accomplished; as he stated with uncharacteristic immodesty:

However sublime were the researches on fluids, to which we are indebted to Messrs. the Bernoullis, Clairaut and D'Alembert, they flow so naturally from my general formulas that one cannot but admire the agreement of their deep meditations with the simplicity of my principles, from which I extract my two equations, and to which I was immediately led by the first principles of Mechanics.¹⁰¹

The papers themselves had remarkably few figures to explain the principles; these were the early days of “pure analysis” that would in part supplant the more geometrical treatments by earlier mathematicians, and would see its apogee in Lagrange’s *Mécanique analytique* (Analytical Mechanics).¹⁰² Euler defined an infinitesimal element of fluid as the simplest shape he could use, the parallelepiped, shown in greater detail than Euler provided in figure 3.19. Of particular interest is the point of origin of the coordinate system; Euler used a fixed frame of reference to describe the pressure field, the system generally used today (Lagrange later developed, in *Mécanique analytique*, a moving frame of reference for fluids).

Euler carefully divided his analysis into kinematics (speed and momentum) and dynamics (forces and accelerations). The kinematic demonstration showed that the mass continuity for an ideal fluid (i.e., incompressible, without friction or rotation) would be a function of the density $\times$ volume V (i.e., $\rho \, dx \, dy \, dz$) and the pressure p . He neatly summarized the differential continuity equation for the element in a fluid at velocity $\mathbf{v} = v_x \mathbf{v}_x + v_y \mathbf{v}_y + v_z \mathbf{v}_z$ as

$$\frac{dp}{dt} + \rho \left(\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z} \right) = 0.$$

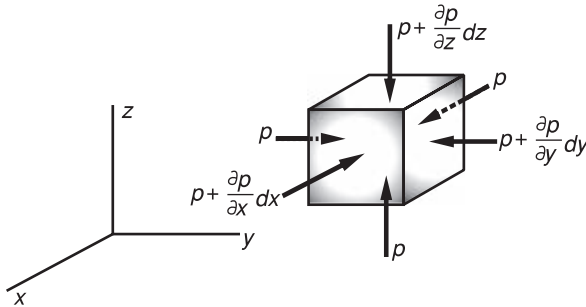


Figure 3.19

Infinitesimal fluid element (parallelepiped).

Choosing the z-axis down, Euler set the acceleration from gravity as -1 . He then went on to develop the dynamics, showing how the acceleration of the fluid (i.e., dv/dt) is related to the differential change in pressure across the volume of the element (i.e., dp/dV) by three linked equations:

$$\begin{aligned}\frac{\partial p}{\partial x} &= -2 \left(\frac{\partial v_x}{\partial x} v_x + \frac{\partial v_x}{\partial y} v_y + \frac{\partial v_x}{\partial z} v_z + \frac{\partial v_x}{\partial t} \right) = -2 \frac{dv_x}{dt} = -2a_x \\ \frac{\partial p}{\partial y} &= -2 \left(\frac{\partial v_y}{\partial x} v_x + \frac{\partial v_y}{\partial y} v_y + \frac{\partial v_y}{\partial z} v_z + \frac{\partial v_y}{\partial t} \right) = -2 \frac{dv_y}{dt} = -2a_y \\ \frac{\partial p}{\partial z} &= -2 \left(\frac{\partial v_z}{\partial x} v_x + \frac{\partial v_z}{\partial y} v_y + \frac{\partial v_z}{\partial z} v_z + \frac{\partial v_z}{\partial t} \right) - 1 = -2 \frac{dv_z}{dt} - 1 = -2a_z - 1.\end{aligned}$$

These two sets of equations—continuity and dynamics—allowed fluids to be analyzed under all circumstances, providing the equations could be integrated. Joseph-Louis Lagrange, who had succeeded Euler as president of the Berlin Academy of Sciences, developed a more general formulation using the stream function and velocity potential, which allowed these equations to be integrated in a more straightforward manner.¹⁰³ Other scientists, such as Jean-Charles de Borda and Pierre Laplace, would continue to add to the body of knowledge through the turn of the century. But certainly by the 1760s, the major elements of a generalized theory of fluids were in place.

Nevertheless, it was recognized that these general equations did not give meaningful answers to practical problems of either hydraulics or hydrodynamics. Specifically, a reasonable theory of fluid friction was lacking, and would not be addressed with any rigor until Charles Augustin de Coulomb's work in the early 1800s. Instead, the emphasis now shifted to experimentation.

Experimentation

The first reports of towed model experiments appeared in the late 1600s, although the practice of towing models in a basin to assess which hull shapes were faster or slower probably extends back into antiquity; Leonardo da Vinci had carried out such experiments in the late 1400s, though he never made those (or any other) results public.¹⁰⁴ These towed model experiments were necessarily qualitative in nature, as the means to measure force—the dynamometer—was not developed until 1826 by the French engineer Gaspard de Prony, and not perfected for measuring ship resistance until the 1870s by the British engineer William Froude. Nonetheless, these towing experiments were surprisingly sophisticated almost from the start. They generally took the form of

a model being attached, by a line through a series of pulleys, to a falling weight that provided the towing force (a later development used a rotating arm), and timing the run with a pendulum. Model experiments as a means of establishing performance or developing theory were by no means limited to ship hydrodynamics; Italian and French hydraulic engineers such as Giovanni Poleni (in the 1710s) and Antoine Chézy (in the 1760s) routinely used small-scale models of canals and pipes in their work on transport and water supply, and in the 1750s the British engineer John Smeaton carried out extensive model tests on watermills and windmills.¹⁰⁵ In broad terms, towed model experiments fell into two categories that often overlapped considerably: assessment of hull forms and understanding of fundamental principles of rational fluid mechanics.

Assessment of Hull Forms

Although the model tests under Colbert and Tourville at Versailles, Brest, and Toulon from 1681 to 1686 (see chapter 2) effectively marked both the beginning and the end of such efforts in France, such tests were pursued, if haphazardly, in other parts of Europe. Around 1675, the English economist Samuel Fortrey, while consulting for the Southampton canal project, constructed and towed a series of twelve flat plain and pointed parallelepipeds, and one teardrop shape, arriving at the conclusion that a long, thin shape would be faster than a short, fat one.¹⁰⁶ Secretary of the Admiralty Samuel Pepys noted a series of experiments carried out in the garden of William Petty before 1685, by the military engineer Henry Sheeres and the constructor Anthony Deane, at the instigation of King Charles II, an avid yachtsman. They compared the towing speed of planks cut in the shape of the waterlines of seven different ships, including Deane's small frigate *Greyhound*, a galley, and a Dutch ship. Each plank was pulled in a 25-meter trough by a falling weight, timed by a pendulum, and run eight or nine times. The fastest ship, at 100 seconds, was the long, thin galley; *Greyhound* came in third at 128 seconds, and the Dutch ship was slowest at 152 seconds, confirming that long, thin, and sharp-ended ships were fastest.¹⁰⁷

Reports of model tests began appearing again only in the mid-1700s (the previously mentioned "solid of least resistance" tests at Deptford apparently left no written records). In the early 1750s, a Thames constructor named Mr. Bird carried out side-by-side tests of different hull shapes in a 10-meter tank, as shown in figure 3.20. The models were circular in cross section, about 80 centimeters long, and built in sections so that their shapes could be changed in a methodical fashion; however, the tank sections were quite narrow in relation to the models, causing blockage that, as we know today, produces results different from open-water tests. Bird's experiments, reported without attribution in the second edition of Mungo Murray's *Treatise on Ship-building*

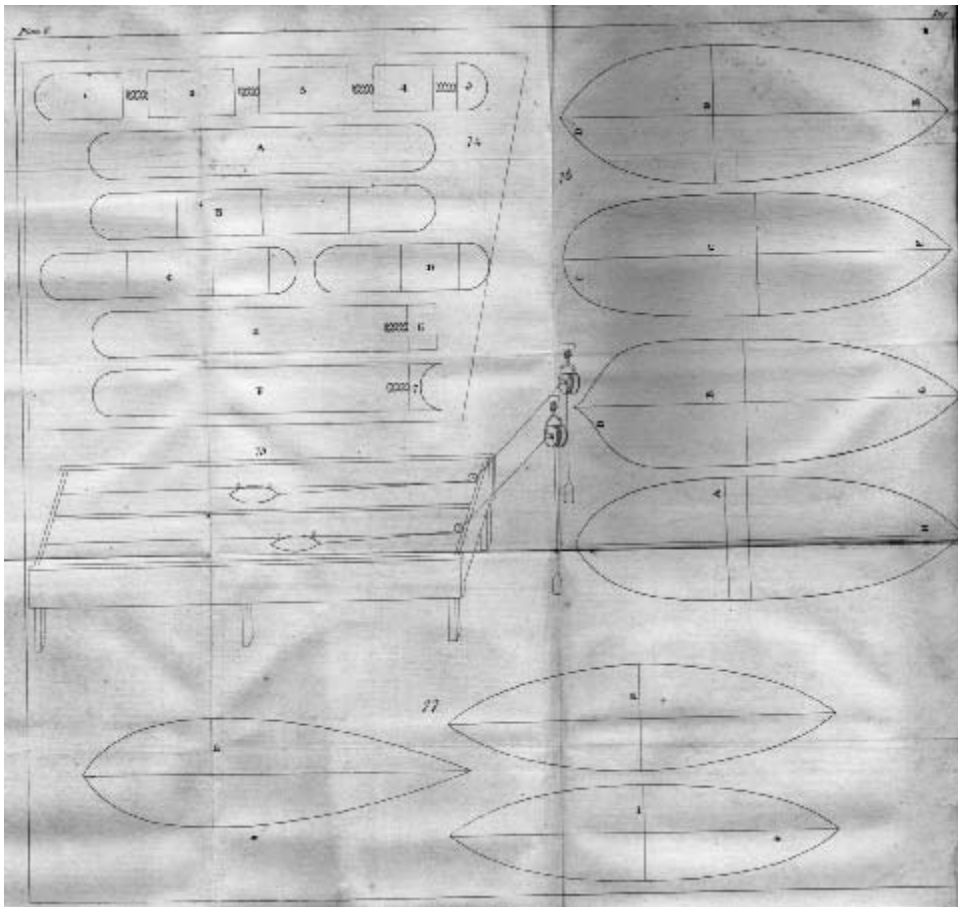


Figure 3.20

Experimental apparatus of Mr. Bird, 1750s. (Murray, *Treatise on Ship-building and Navigation*, 2nd ed. [1765], plate V) Credit: Cushing Library, Texas A&M University.

and Navigation, indicated that the towed models with the widest section forward always encountered the least resistance, which he noted was in keeping with Newton's "blunt-headed figure." In fact, this result was probably due to blockage effects in the narrow tank, as later experimenters using open-water apparatus would find that the "best" position for the widest section varied with speed.¹⁰⁸

From 1758 to 1763 the newly formed Society for the Encouragement of Arts, Manufacture and Commerce in London, a group of private citizens organized under William Shipley, sponsored a contest for the fastest and most stable hull designs, as part of its overall strategy to award prizes for improvements in agriculture, chemistry, manufacturing, and mechanics. To determine the winner, the Society devised a sophisticated and expensive series of model tests to compare the entries; ultimately, two 74-gun and four 32-gun models were entered by (apparently) amateur builders. The first tests used a 4-meter circulating water tank, based on the apparatus employed by John Smeaton to test his water mills, but these results were inconclusive and never recorded. A second series of side-by-side smooth-water towed trials, propelled by falling weights and timed with stopwatches, was conducted in the fishpond of Peerless Pool near Old Street in the City of London. A third series of rough-water towed trials was conducted in a pond near Epping Forest outside London. When these results were combined with a set of stability tests, the Society made two awards, of £100 and £20 (about \$16,000 and \$3,200 in 2002). Although some naval officers were present at the trials, it is not clear whether the winners were ever able to sell their designs to the navy or private constructors.¹⁰⁹

In the Netherlands, the Rotterdam naval constructor Pieter Pauluszoon van Zwijndregt used a series of tests he conducted in the 1750s to develop his hull lines. As he described in his unpublished manuscript of 1757, Zwijndregt made a series of 1.5-meter-long planks sawed into the shapes of waterlines, and towed them in a 50-meter open-water basin. His testing apparatus was relatively sophisticated. In addition to being performed in open water and having a fairly long run to obtain steady speeds, he also took the unprecedented step of connecting the models with lines at both ends to keep the model "in track"; in experiments such as Bird's, where the aft end ran free, the model was susceptible to yawing motions that could affect the reliability of the results. Although he methodically tested various shapes to determine least resistance, Zwijndregt did not try to distill general formulas from these experiments; he was interested only in practical results, and these tests gave him a series of hull lines, which he numbered for use in his various designs.¹¹⁰

The Swedish constructor Fredrik Henrik af Chapman, during seven years abroad, visited Dutch dockyards in 1754, and quite possibly saw Zwijndregt's towing

experiments; this may have inspired his own efforts some 20 years later.¹¹¹ Certainly there were similarities between Chapman's towing apparatus of the 1770s and that of Zwinjndregt; the tests were over a large stretch of open water; and, most tellingly, both sets of models had aft lines to keep them in track (figure 3.21). However, both Chapman and Zwinjndregt were silent on any meetings between them, and there is no way to prove or disprove any link.

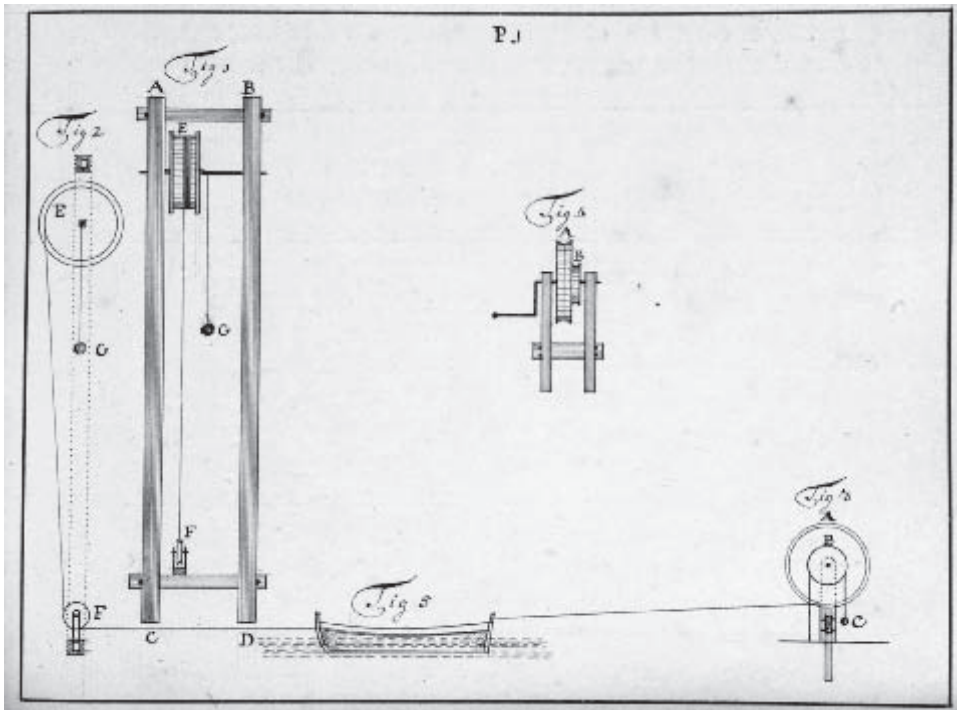
Chapman's testing procedures were quite thorough: towing seven different shapes (each around 70 centimeters long) over a 20-meter stretch of water, using four different weights several times each, measuring over 300 separate results with a stopwatch instead of a pendulum. He described the test results in his 1775 *Tractat om skeppsbyggeriet* (Treatise on Shipbuilding), preceding them with a lengthy explanation of resistance theory that borrowed heavily from Newton's solid of least resistance. Chapman developed a formula relating resistance and water velocity to the position of the greatest breadth, and then tried unsuccessfully to confirm it with the test results in order to develop the proper proportions for ships. His observations were as follows:

- At slow speeds, resistance is least with the sharp end forward.
- At higher speeds, there is a crossover, and resistance becomes least with the blunt end forward.
- Thus, the required velocity should determine the position of greatest breadth.

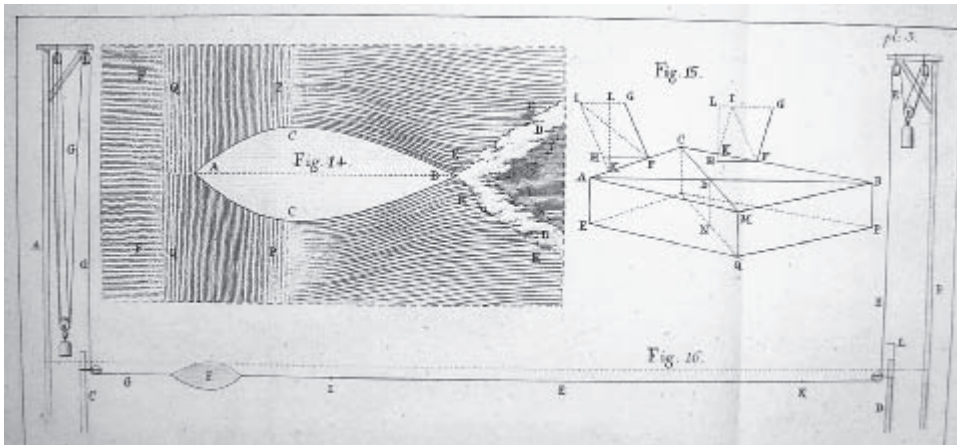
Chapman noted that these results could not lead to any conclusions about the proper form of ships, and went on to develop a more comprehensive set of factors for admeasurement: length, breadth, midship sections, and others.¹¹²

Chapman "retired" from naval service in 1793, after Sweden drew to a stalemate with Russia and its navy was already beginning to decline; but in fact, he was soon busier than ever. In 1794 he received a state grant to continue his resistance experiments, and he had a 20-meter-long tank built on his estate. Over the course of that summer, he had sixty-six 2-meter models built, and conducted over 500 meticulously tabulated experiments, which he published the following year (figure 3.22, top). Following from his previous work, Chapman was trying to discover a relationship between the size and angle of the bow and stern, and their resistance. What he determined, from varying the angles of entrance and run, was that the stern's shape was most important, and that resistance was a minimum when the stern run formed an angle of 13°17' with the centerline. From this, he developed his "relaxation method" of construction.¹¹³

Although officially retired, Chapman designed—and convinced the Admiralty to build—three ships to this "relaxation method": the 10-gun brig *Svalan* in 1797, the



a



b

Figure 3.21

Towing experiments in the Netherlands and Sweden. Top: Experimental apparatus of Pieter Pauluszon van Zwijndregt (1750s). (Zwijndregt, *De groot Neederlandsche scheepsbouw* [1757].) Credit: Nederlands Scheepvaartmuseum, Amsterdam. Bottom: Apparatus of Fredrik Henrik af Chapman (1770s). (Chapman, *Tractat om skepps-byggeriet* [1775], plate 3). Credit: U.S. Navy Historical Center.



b

Figure 3.22 (continued)

74-gun ship *Försiktigheten* (later called *Konung Gustaf IV*) in 1799, and the 40-gun frigate *af Chapman* in 1803. Chapman carried out a series of at-sea trials to determine the effectiveness of his “relaxation method” for *Svalan* (figure 3.22, bottom) in the summer of 1803, although by then he was 82 years old. The trials were only subjective judgments of the ship’s performance, and not side-by-side tests with other ships.¹¹⁴ Although he was disappointed by the results, he nevertheless published them in an 1806 book, with a full explanation of why his technique failed, stating that the restriction on the stern lines forced him to design a wider forward section that hindered the ship’s maneuverability.¹¹⁵

Chapman went on to recommend that instead of using the “relaxation method” for a ship’s lines, one should instead use his “parabola method” of construction, introduced in his 1775 *Tractat*, which approximated the distribution of underwater hull volume in the shape of a parabola. This concept made it easier to design the hull but had no basis whatsoever in hydrodynamic theory. Nevertheless, the “parabola method” or “parabolic system” of construction was sporadically proposed and adopted through the 1860s, by Europeans including the prolific Trieste constructor Gaspare Tonello, as well as by Americans such as the clipper ship designer John W. Griffiths and the Swedish émigré naval constructor John W. Nystrom.¹¹⁶ The first attempts to use model experiments to develop successful hull forms thus drew to a rather disappointing close; it would not be until William Froude’s work in the 1870s, and methodical series developed in the United States and elsewhere in the early 1900s, that different hull form parameters could be evaluated critically. The use of model tests to understand rational fluid mechanics was scarcely more successful.

Understanding of Fundamental Principles of Rational Fluid Mechanics

The towed-block experiments conducted by Christiaan Huygens in 1668 to confirm the v^2 law predated the ship model tests conducted in Britain at the time of Samuel Pepys. But towed model tests were quite rare at the time; instead, the shock theory of fluid resistance seemed to lend itself more to testing by the percussion apparatus, where the impact of a fluid stream (air or water) on a plate was balanced against a static weight to estimate its force. The percussion apparatus had its limitations, however, and no one understood this better than Benjamin Robins. A British mathematics professor and military engineer, Robins became interested in ballistics in the 1730s and began applying the theoretical work of the Bernoullis and others in developing more accurate means of predicting the fall of shot from cannon. He divided his research into two areas: internal ballistics, defining the projectile’s muzzle velocity as a function of its mass, gunpowder charge, and barrel geometry; and external

ballistics, accounting for air resistance in determining the flight path of the projectile. For the first part, Robins developed the “ballistics pendulum,” a flat plate connected to a rigid arm that was placed in front of the cannon. By observing the arc of swing when the projectile hit the plate, Robins could determine the projectile’s muzzle velocity and air resistance at high speed (now known to be supersonic). But this percussion apparatus was not sensitive enough to measure the projectile’s air resistance at lower (i.e., subsonic) speeds, which was necessary to predict its trajectory.

External ballistics had been the province of mathematicians since Galileo, who routinely discounted air resistance because conventional wisdom held that it was negligible. Robins showed that a 24-pound cannon with a theoretical range of 25 kilometers actually lobbed shot less than 5 kilometers; air resistance was in fact of considerable importance. To measure it, Robins designed and had constructed a machine with a wooden rotating arm of about 1.3 meters, to which a cannonball was attached (figure 3.23). A descending weight attached to the brass barrel spun the apparatus. Robins equated the product mv of the falling weight with the mv of the whirling projectile plus arm; subtracting out the values he obtained for the whirling arm alone gave him the resistance of the projectile. From these experiments, he not only confirmed the v^2

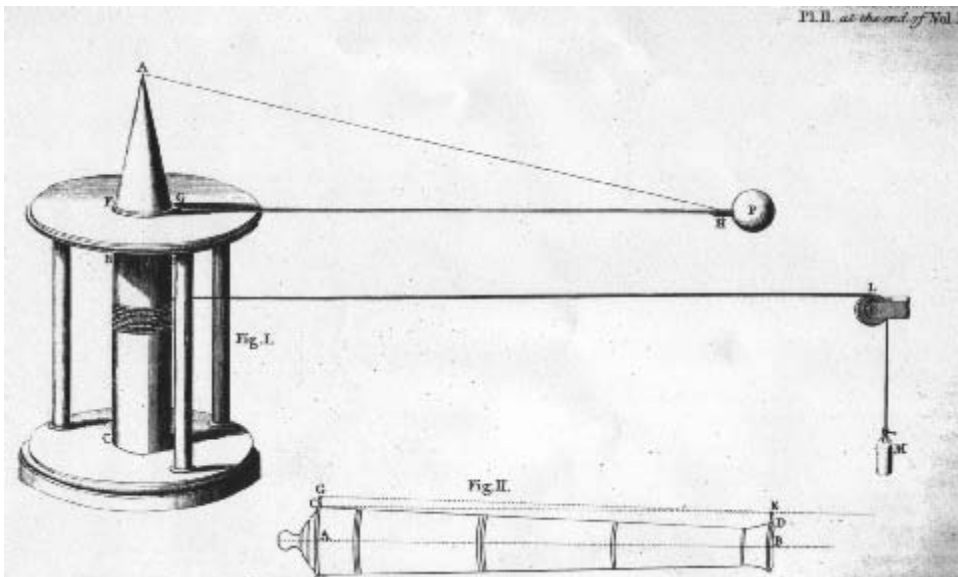


Figure 3.23

Robins's rotating arm apparatus (1742). (Robins, *New Principles of Gunnery* [1742/1761], plate 1). Credit: Burndy Library, Cambridge, MA.

laws for resistance but also developed empirical data for differing shapes and geometries of projectiles, which were published in 1742 as *New Principles of Gunnery*.¹¹⁷

Robins became widely respected for his work, and his experimental apparatus was quickly copied; for example, John Smeaton used a rotating arm in his 1752 windmill experiments. It also caught the attention of Jean-Charles de Borda, a young French cavalry officer who fought in the Seven Years' War, and became an associate member of the Academy of Sciences on the strength of his theoretical work on ballistics. After joining the army's Corps du Génie (Corps of Engineers), responsible for military projects, Borda was assigned to the fortified city of Brest in 1762. His mathematical abilities were noticed by the intendant of the Brest dockyard, Aymar-Joseph, count of Roquefeuil-Kerlouet, a founder of the Académie Royale de Marine (Royal Academy of Navy).¹¹⁸ Roquefeuil was a champion of scientific developments in naval architecture, having recently sponsored an inclining experiment on the 110-gun ship *Royal Louis* (described in chapter 4). Although Borda was still an army officer, Roquefeuil supported his proposals for a series of experiments on fluid resistance, which were conducted in 1763 and 1767. Borda's test apparatus was little different from Robins's, though he gave no credit to him.

The 1763 experiments on air resistance, actually carried out in Dunkirk, were in keeping with Borda's army background and interest in ballistics, and were aimed at proving or disproving Newton's v^2 and $\sin^2$ laws of resistance due to fluid shock, of which Borda was skeptical.¹¹⁹ Using different falling weights as the motive force, he placed flat planes of different sizes, as well as prisms, cylinders, and cones, on the whirling arms, and timed the rotations in air. Those first tests clearly established that the v^2 law held, but that the resistance of inclined planes varied not as $\sin^2$ but only as the sine of the angle of attack.¹²⁰

By 1767, Borda had resigned his army commission and been made a navy lieutenant. His second set of experiments, less thorough than the first, was more clearly aimed at naval applications. His new rotating arm towed various bodies—flat plates and spheres, among others—around a 4-meter-diameter basin (figure 3.24). In this series, he compared (among other things) the resistance of bodies both fully submerged and moving on the surface. Whereas Newton predicted that the resistance of a sphere was half that of a flat plate, Borda found the factor to be 0.4; he thus concluded that shock theory was “absolutely false, that the results are very far from the truth, and consequently it is useless and even dangerous to wish to apply this theory to the art of the construction of vessels.”¹²¹

Almost hidden in the memoir is the observation that a body towed on the surface exhibits more resistance than one fully submerged, and that resistance increases faster

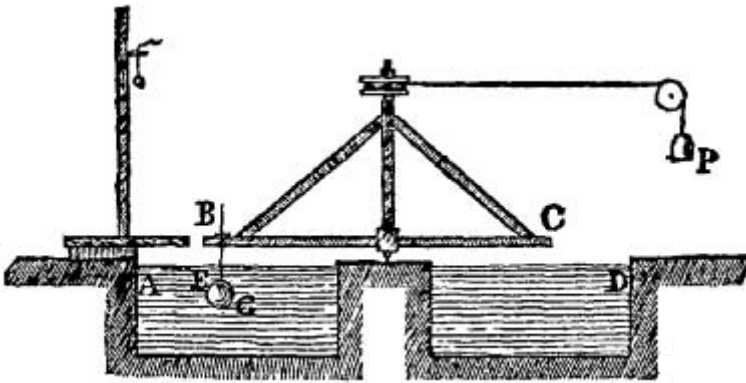


Figure 3.24

Borda's rotating arm apparatus for testing in water (1767). (Borda, "Expériences sur la résistance des fluides" [1767], p. 495). Credit: Bibliothèque Nationale de France/Gallica.

than the v^2 law. Almost exactly 100 years later, the British engineer William Froude would base his ship resistance theories on just such differences between fully submerged and floating bodies, and derive his now famous laws of separation of resistance into friction and wavemaking components. Borda, however, assigned the higher surface resistance to a greater loss of *vis viva* and appeared to give it no more thought.¹²²

This anomaly, along with the general paucity of results on water resistance, continued to trouble Borda, but his shipboard assignments and work on hydrography left him no time to continue his experiments. In 1768 he was in the port city of Lorient (home of the Compagnie des Indes or East Indies Company) with the mathematician Etienne Bézout, examiner of the Navy Guards, on an annual inspection of naval officers, when he met the captain of the port, Antoine-Jean Marie, count of Thévenard. Thévenard, who was aware of Borda's 1763 experiments, listened with interest to accounts of Borda's latest ones and volunteered to continue the research in Lorient. Later in 1768, with two bright young officers to assist him, Thévenard succeeded in obtaining funds from the navy, and equipment and labor from the East Indies Company, to dig and equip a 70-meter canal, about 4 meters wide and 3 meters deep, parallel to the right bank of the Scorff River (figure 3.25).¹²³ This would be the largest purpose-built testing basin ever constructed until William Froude's tank in Torquay was erected in 1870.

Thévenard and his assistants spent a year on this considerable engineering effort, which was made more difficult by the frequent rains, and the experimental efforts

were no less daunting.¹²⁴ Under the occasional surveillance of Borda and Bézout, they began tests in September 1769. Three years later their work was complete; Thévenard and his team had tested 52 different solids, including not only basic shapes such as cubes, prisms, and cones, but also Newton's and Bouguer's solids of least resistance (each solid was fairly large, almost a meter wide). To further examine the surface resistance phenomena, they towed many of the solids both at the surface and at varying depths. They also took very careful note of particular observations that could explain the detailed data they were recording.

Some key results and observations of the experiments were the following:¹²⁵

- As Borda had noted, solids towed at the surface have greater resistance than submerged bodies, but Thévenard attributed the increase to friction against the solid caused by the agitation of the waves. This would be the last series of experiments that compared the resistance of submerged and surface bodies until William Froude's and William Rankine's work in the 1860s–1870s.
- The depth of submergence of a solid had no effect on resistance.
- Bouguer's elliptical bow of least resistance did, in fact, give the least resistance compared with any other shape—including Newton's frustrum.
- Elliptical bows offered the least resistance because the wave pushed in front of the bow is elliptical; an elliptical bow will therefore push the minimum amount of water before it.
- An elongated stern offered less resistance than a shortened one.
- Both model and full-scale experiments for the bow shape on a 26-gun frigate showed that a cutaway forefoot (i.e., where the stem angles aft below the waterline) gave less resistance than a vertical bow.

It was to its credit that the East Indies Company initially granted the equipment and valuable labor for these experiments. The results, while demonstrating certain insights into the nature of fluids, also would have had immediate applicability to East Indies Company ships (e.g., the advantages of an elongated stern and cutaway forefoot). Unfortunately, all activities of the Company were suspended by bankruptcy in 1769, just as the experiments began, and Thévenard completed his research as a navy captain.

Even more unfortunately, this remarkable set of experiments received no public notice for almost thirty years.¹²⁶ Just five years later, the hydrodynamics expert Charles Bossut learned about Thévenard's work through secondhand sources.¹²⁷ Thévenard would not publish his complete results until 1800, at the start of the Napoleonic Wars that raged through Europe. Little attention was paid to them outside France, and

furthermore, they were only one part of a ponderous four-volume set of memoirs on many subjects.¹²⁸ Almost no subsequent literature on hydrodynamics referred to Thévenard's work.¹²⁹ Instead, the later experiments by Bossut, Pierre Du Buat, and Nicolas Romme took center stage.

It was an interest not in the speed of ships but in the economics of canals and river-boats that led to the most famous of these experiments in hydrodynamics. The brilliant economist Anne-Robert-Jacques Turgot was named by Louis XVI to be comptroller of finance in 1774, after a two-month stint as minister of the navy. Turgot saw the improvement of canals (along with bridges and roadways) as means of increasing France's prosperity, as part of an overall reform policy that would later go disastrously wrong. For some time, a proposal had been in the planning stages to construct the 14-kilometer Picardy Underground Canal, in order to open the trade of Flanders (now Belgium) with Paris and the Rhône basin, as well as to provide easier transport of war materiel to the northern borders of France. The practical problems of towing boats in narrow and shallow waters were well known but not well quantified; and when Turgot came to office, he naturally questioned whether the enormous expense of tunneling would result in an actual increase in trade if boats could not navigate the much smaller underground canals faster than a system of wider surface canals with locks.

Turgot was an economist and not a scientist, so he turned to the person closest to him who could understand the science behind inland navigation, Marie-Jean de Caritat, marquis of Condorcet, the young mathematician and member of the Academy of Sciences whom Turgot had made his inspector general of the mint, Condorcet, well versed in calculus but not in physics, suggested that a commission consisting of himself, Charles Bossut, and Jean Le Rond D'Alembert should examine the problem. Bossut had recently written a textbook that illustrated both theoretical and experimental approaches to the problems of hydraulics, pointing out the need for experiments to be run at sufficiently large scale to give valid results. He was therefore an obvious choice to carry out the experiments. D'Alembert, although a theoretician and not an experimenter, was chosen to give respectability to the project.¹³⁰ The committee was formally set up in the summer of 1775, with the overall charge now expanded to "examine . . . the means for perfecting the inland navigation of the kingdom."¹³¹ The experiments were divided into two groups, the first dealing with wide, deep waters, as on rivers, and the second dealing with narrow, shallow waters, as in canals.

By good fortune, Bossut and the others already had an insight into the anomalous behavior of boats in shallow water, having read a 1768 letter on the subject by the

American scientist and politician Benjamin Franklin, written while he was living in Britain. Some years earlier Franklin had been traveling in Holland and learned that horses had more trouble pulling canal boats in shallow water even when the boats did not touch bottom, a fact he confirmed by talking to Thames watermen. Curious about this, Franklin built a 4-meter wooden trough with a movable bottom, so that he could make the canal deeper or shallower. A shilling coin acted as the motive force for a 15-centimeter wood block, and Franklin, not having a watch, counted time on his fingers. The results of this crude little experiment showed that the shallowest water caused a 20 percent increase in the time needed to tow a boat over a set distance.¹³²

Bossut and his colleagues chose a 30-meter basin on the grounds of the newly built École Militaire (Military School) in Paris, then merely a set of barracks, as the site for their tests. On one side of the basin they erected a 25-meter tower (about eight stories tall) with falling weights that allowed a maximum run of about 21 meters over the length of the basin (figure 3.26). The first set of open-water tests was run directly in the basin. After these tests were completed, they built within the basin a 24-meter wooden canal having a movable floor and sidewalls, to run the second set of shallow- and narrow-water experiments. A total of 293 trials were conducted (201 in open water, 66 in shallow water, 9 in narrow channels, and 17 additional tests), using 22 models ranging from 1 to 2 meters in length and having flat and angled bows. All the models were towed on the surface.

The group noted the effects of narrow and shallow canals, confirming Franklin's observation that shallow water caused an increase in drag and making specific measurements of the effects of blockage.¹³³ Although the recommendations were rather vague, simply stating that canals should be as wide and deep as possible, they did come down firmly against the idea of a subterranean canal.¹³⁴

The principal focus of the report was directed to the open-water case, and the results can be summarized as follows:¹³⁵

1. Neither the v^2 nor the $\sin^2$ law held at the surface. Resistance was seen to increase at a faster rate than v^2 or $\sin^2$. The committee assumed that this was due to the fact that as the speed increased, the bow wave rose above the level of the surface. To this end, they made several measurements of the bow wave both at the ship and some distance away, as well as the resulting depression of water at the stern; however, no clear correlation was established.

2. For flat plates towed underwater, the resistance could be expressed as

$$R = 1/2\rho v^2 A,$$

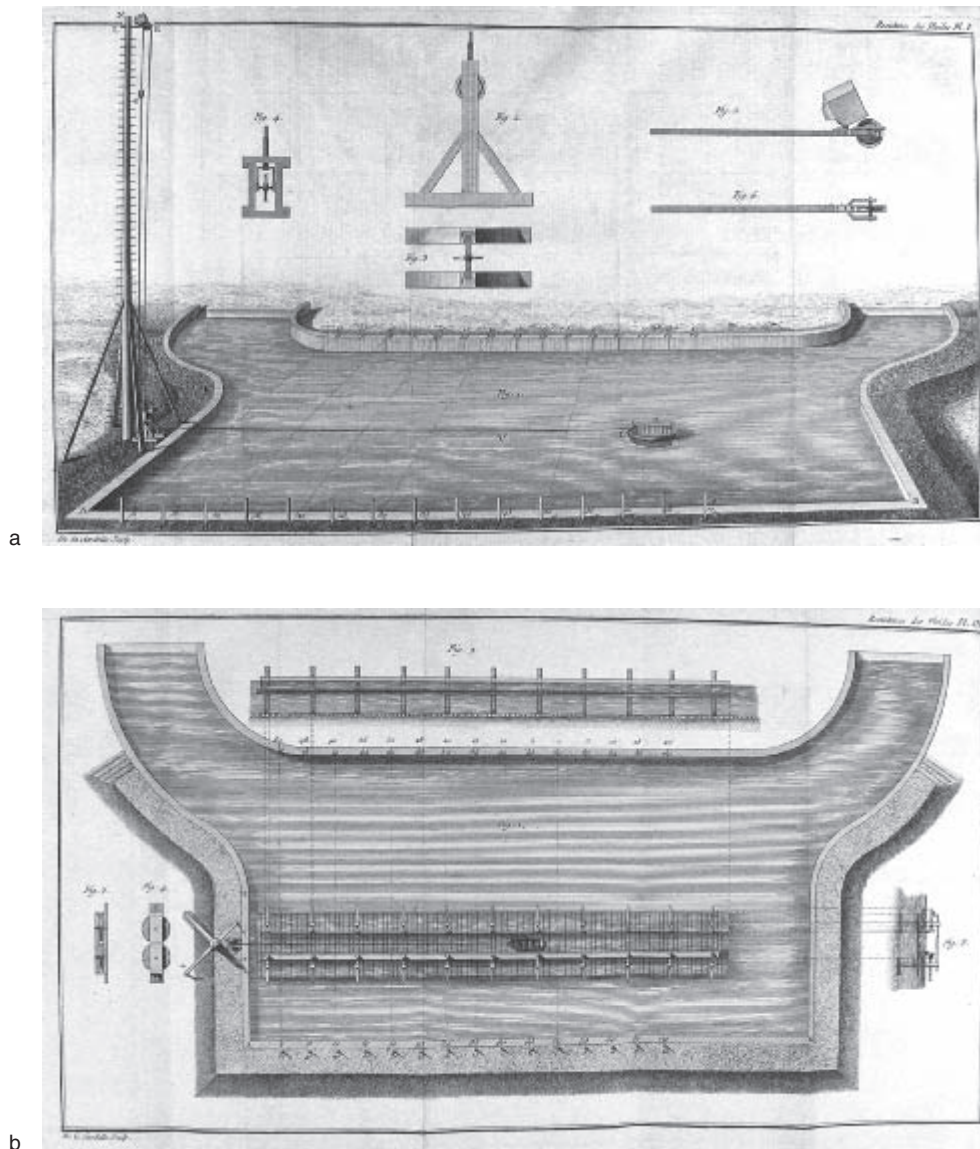


Figure 3.26

Bossut's experiments at the Military Academy, Paris (1775). Top: General view with open-water setup. Bottom: Shallow-water setup. (Bossut, D'Alembert, and Condorcet, *Nouvelles expériences sur la résistance des fluides* [1777], plates I and III). Credit: Burndy Library, Cambridge, MA.

half that predicted by Newton. This was the same result that Euler had postulated in his 1749 *Scientia Navalis*, essentially adding a “1/2” to Bernoulli’s *vis viva* equation, almost a century before Coriolis did the same to develop the modern version of kinetic energy.

3. Bow resistance was the dominant factor; “the whole friction against the sides, bottom and rudder will vanish in comparison with the resistance of the bows,” and was indistinguishable from the resistance of the pulleys and air.

In 1778, Bossut and Condorcet continued with a second series of experiments a few hundred meters from the first ones, in a 60-meter-by-30-meter sewer reservoir in Chaillot, across the Seine from the present-day Eiffel Tower. The goal was to answer the following questions:

1. Do curved bows follow the same laws as angular bows?
2. Does a longer or a shorter stern influence resistance?
3. Does the length of the vessel influence resistance, assuming a constant cross section?
4. Will a small, triangular point on a flat bow increase or decrease resistance?

For the first question, the results showed that curved bows did not obey the same laws as angular bows, but no specific set of laws could be derived. The answer to the second question was that a longer stern increased a boat’s speed, but again, no specific laws were developed. For the third question, Bossut found that a length-to-beam (L/B) ratio of 3 was optimal for the speeds they tested, but glossed over the fact that, according to previous results, this should have had no effect (i.e., the bow resistance should have been overwhelming). Finally, a triangular point fixed to the bow did reduce resistance.¹³⁶ This last observation, somewhat analogous to a modern surface-piercing bulbous bow, was evidently never taken further in practice.

These series of experiments, with such famous authors, received wide attention and had considerable influence.¹³⁷ This was most notable in the continued assumption that bow resistance overwhelmed other parts of a ship. The experiments were cited in many naval architecture texts and translated into English by the British Society for the Improvement of Naval Architecture some years later, even after the later experiments by Mark Beaufoy, sponsored by the same Society, gave considerable differences from those results.

The hydraulic experiments of Pierre Louis Georges Du Buat also received wide recognition, though by a different readership. Du Buat, like Borda, was a member of the Corps of Engineers, specializing in canal and harbor development. As part of this, he

carried out a wide-ranging series of model experiments aimed at deducing basic laws for water movement in rivers, canals, and conduits, and the effects of bridges, dams, locks, and weirs on this movement. The experiments were reported in *Principes d'hydraulique* (Hydraulic Principles), first published in 1779, and revised and expanded several times; the 1786 edition received praise from George Washington, a former surveyor, shortly before he became the first U.S. president. Du Buat was aware of the previous work by Bossut on water resistance in channels,¹³⁸ but found that it did not address his needs. In particular, Du Buat identified the resistance of the conduit bed and walls as the major area of concern. Using pipes and channels of various configurations and materials (wood, glass, tin, etc.), he showed that friction was independent of pressure; rather, it varied nearly as a function of v^2 . His experiments led him to believe that this friction was independent of surface roughness, though this was later shown to be incorrect. Rather, he introduced the concept of hydraulic radius (the ratio of the channel cross section to its wetted perimeter) to define channel flow, a measure used to this day.¹³⁹

Du Buat's work on the resistance of floating bodies received somewhat less attention, but was remarkable for two reasons: (1) his measurement of resistance using dynamic pressure and (2) his division of ship resistance into separate components, including friction. Although D'Alembert had expressed resistance as a function of pressure 25 years earlier, Du Buat was the first to actually use this principle in resistance experiments. To do this, he employed the device developed in 1732 by Henri de Pitot, nowadays called a Pitot tube and used to measure flow velocity (figure 3.27).¹⁴⁰ Pitot, who (as described in chapter 2), had simplified Johann Bernoulli's analysis of maneuvering into practical tables for pilots, came up with this instrument that measured velocity by comparing the height of water in two manometers, one exposed to the flow (dynamic pressure) and the other shielded from it (static pressure). He had proposed it to replace the traditional ship's log, but the difficulties of having tubes penetrate a ship's hull made it impractical.¹⁴¹

Du Buat used Pitot's tubes as a central part of his experimentation, attaching them at the front, sides, and back of bodies set into a stream of water. He found that there was a considerable overpressure at the front of a body, a negative pressure or suction at the back, and uniform variation of the pressure along the sides from front to back. The resistance from the variance in pressure he termed "retrograde," and he gave it the hydraulic representation of a "slope" of water, from where it piles up in front of the bow to where it dips down to a trough at the stern.¹⁴²

Du Buat assumed that a ship would be subject to three different forms of resistance: bow shock, based on Newton's concept; lateral friction of the hull, derived from his

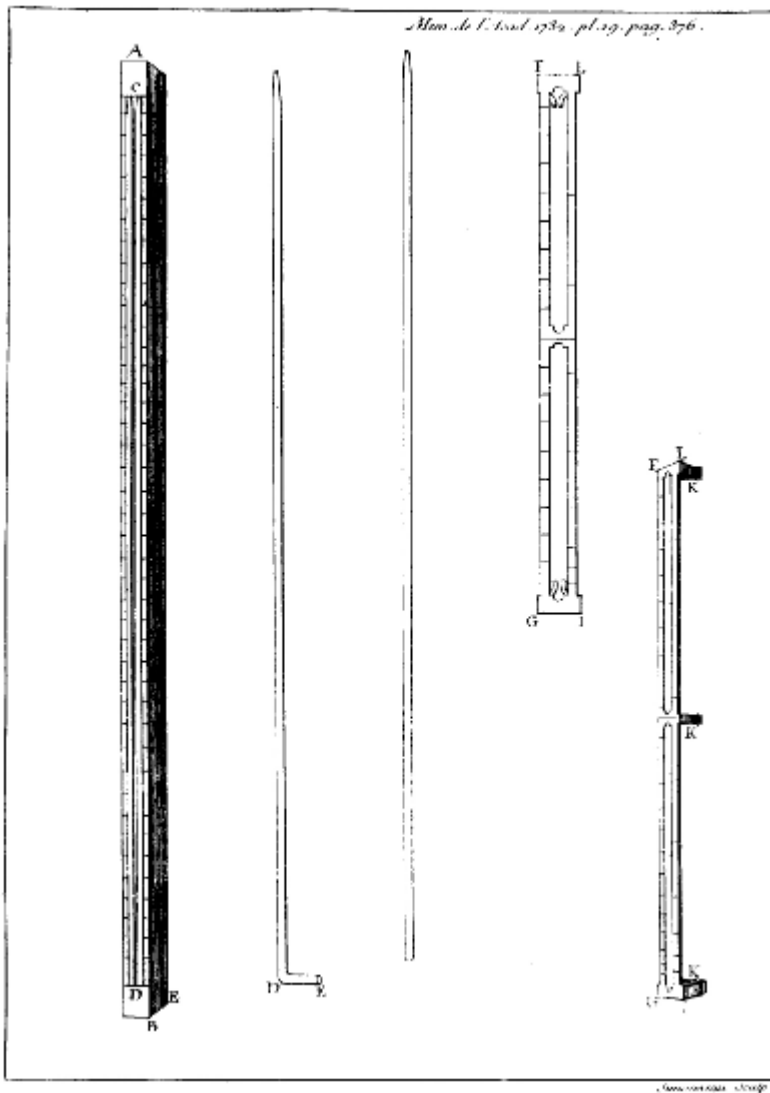


Figure 3.27

Pitot's instrument for measuring velocity (1732). (Pitot, "Description d'une machine pour mesurer la vitesse des eaux courantes" [1732], p. 376). Credit: Bibliothèque Nationale de France/Gallica.

own work on channels; and “retrograde” resistance. Du Buat’s measure of resistance was in units of cubic *pieds* of water, which could be converted to pounds of force. He made various calculations of the contribution of each component, which differed depending on the ship.¹⁴³

1. Bow shock 40–60 percent
2. Lateral friction of the hull 20–30 percent
3. Retrograde force 15–25 percent

A modern naval architect would immediately recognize the last two factors as the principal components of resistance, friction, and form drag (discussed in the next section). Du Buat also theorized that canal boats in confined waters carried a fourth component of resistance, the pressure of the water pushed in front of the bow.¹⁴⁴ Du Buat’s work on ship theory never received the widespread attention of his hydraulic work; it is scarcely mentioned in further naval architecture literature, compared with the widespread attention given to Borda and Bossut. Yet his insight into the separation of resistance into components was remarkably prescient, and would not be fully developed for almost a century, though for much different reasons, until William Froude’s work in the 1870s.

On the other hand, the concept of ship resistance based on pressure came simultaneously and quite independently to Nicolas Charles Romme, a mathematics professor for the Naval Guards in Rochefort. By the early 1780s, a plethora of experiments had been conducted on ship resistance, but the results were so varied that it seemed impossible to draw any conclusions. In July 1783, Romme reported to the Academy of Sciences on his extensive study of the experimental results that had been obtained by Borda, Bossut, and Chapman (he evidently never saw Du Buat’s work). He stated that those experiments had focused on the form of the bow while neglecting the stern, which was contrary to his own experience. Romme had himself conducted several experiments at Rochefort in 1776, towing small models and a ship-shaped canoe, and his results suggested that the resistance was the same whether they were towed bow-first or stern-first, which was similar to Chapman’s results but different from Bossut’s. Romme claimed that he had developed a means to reconcile the results of the various experiments.

Romme was a brave man; the Academy panel who judged his memoir included Borda and Bossut, whose results he had criticized. To their credit, they saw some benefit in his work and quickly recommended that the navy fund additional experiments. Romme went to work and reported back to the Academy in six months. He had returned to Rochefort, where in a 60-meter channel, he had set up a towing

apparatus, to which he had attached a rowboat fitted with Pitot tubes at the bow and stern. Romme found that pressure on the bow of a boat in motion was greater than in the at-rest condition, while the stern pressure was less than at rest. From this result, he developed a theory of ship resistance that, for the first time, eliminated any reference to “shock” and instead used only pressure to define resistance.

Romme’s concept was similar to Du Buat’s; every element of a body moving in the water experiences both static pressure p (the depth of immersion of that element) and dynamic pressure, which can be represented as an equivalent height of water h . The static pressure is the same throughout; the dynamic pressure on the port and starboard sides will cancel each other out; thus resistance is a function of the difference in dynamic pressures of the bow and stern. Romme developed the formula for the resistance of a rectangular block:

$$R = \frac{3Kh}{90} \int a dp,$$

where: R = resistance, K = a constant due to fluid “tenacity” (i.e., viscosity), a = width (beam) of block, h = dynamic pressure expressed in equivalent height of water, dp = static pressure of an element at a specific depth; the integration should be from $p = h$ to p = draft, although this was not specified.

Using this formula and variations to account for angled hull forms, Romme said that he could calculate the resistance of a curved shape by using its equivalent chord. He also declared that he was able to accurately reproduce the results of Bossut’s experiments on towed prisms, a claim that was accepted by the Academy reviewers. Romme did not provide any calculations of how he supported that claim, but there are several factors that make the claim dubious. First, the equation is completely in units of height of water, equivalent to pressure, while Bossut’s results were in time of transit, equivalent to speed; there was no way to extract speed from pressure. Second, the viscosity constant K was never specified; it does not appear to have been a frictional coefficient in the form of Du Buat, and its units were never clearly defined. Third, the general form of the equation indicates that a submerged body would encounter greater resistance at greater depths (because the integral would be over a wider range), which was in fact disproved by Borda.

Romme tested his theory on two 3-meter models of the 74-gun ship *Illustre*, one built to the actual ship’s lines, and the other with the same dimensions and midship section, but built as a series of prisms (figure 3.28). His towing experiments showed that the two hulls pulled by equal weights had equal transit times, confirming his supposition that curved lines could be modeled as straight chords. He also found that the

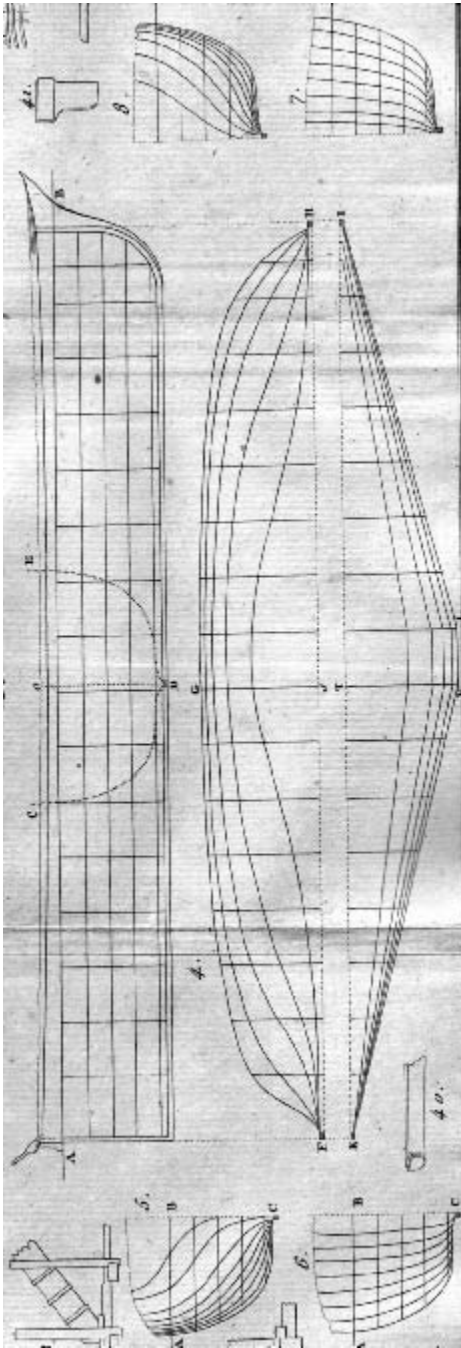


Figure 3.28

Romme's ship models (1783). The top set of waterlines corresponds to a conventional curved hull. The bottom set shows the hull lines modeled as straight chords. (Romme, *L'Art de la marine* [1787], plate A). Credit: U.S. Navy Historical Center.

results were the same whether the hulls were pulled bow-first or stern-first, or even when the bow of one model was attached to the stern of the other. From this, Romme deduced that resistance was principally a function of the midship section, and not of the bow or stern shape. To support this, he pointed to the fact that *Illustre*, with a large midship frame, sailed more poorly than *Fendant*, another 74-gun ship of the same size but having a smaller midship section.

The Academy commissioners, when they finally reported in 1785, were somewhat skeptical of Romme's conclusion that the bow shape was unimportant, but they agreed that the midship section was more important than the bow shape. They recommended that the Academy publish his experiments, and a prize was announced on the subject, but eventually Romme ended up publishing the results himself, in his 1787 *L'Art de la marine*.¹⁴⁵

Downfall of the Solid of Least Resistance

Recapitulation

The shock theory of resistance was short-lived. From its inception in 1687, it passed through several theoretical stages aimed at finding a solid of least resistance, which Bouguer developed from 1727 to 1733 as a bow of least resistance. Both he and Euler expanded this concept from 1746 to 1749, but it was Bouguer's concept of relative impulsions that became adopted under the name "ratio of bow resistance" by French naval constructors in the 1750s (though not by other navies). By 1765, the ratio of bow resistance was required to be included on ships' drawings. Yet there was continued unease over the usefulness of this calculation; ships that, according to theory, should have been fast sailers were often quite slow, and vice versa.

At the same time shock theory was routinely being used by French naval constructors, five mathematicians were effectively laying waste to its underpinnings. From the Bernoullis' works to Euler's grand synthesis, less than 20 years had passed; by 1755, it was clear that fluid movement resulted not in impacts but in streamlines, and resistance was due not to shock but to changes in pressure. This alone was not enough to convince even the most learned French constructors, who had been taught shock theory in school; they needed the results of practical experiments to convince them that their instructors' carefully laid out lessons were, in fact, completely wrong.

Those experiments were not long in coming. From 1754 onward, Zwijsendregt in the Netherlands and Chapman in Sweden were conducting model tests to help them design ships, although the failure of Chapman's theories would not be published until

1806. Rather, a series of widely publicized French experiments from 1763 to 1775 provided convincing evidence that shock theory was wrong. The most critical of these experiments were those of Borda, due not to their rigor but to the later role he would play in the French navy. His statement that shock theory is “absolutely false. . . and even dangerous to wish to apply,” combined with Bossut’s conclusions that neither the v^2 nor the $\sin^2$ law held, provided the second “shock to the system” that had been established by Newton. Unfortunately, no adequate theories of resistance were available to take its place; the work by Thévenard might have led to a better understanding of wavemaking resistance, and the experiments of Du Buat and Romme showed how friction and pressure might have been accounted for, but the French Revolution shut down the overarching Academy of Sciences and put the brakes on further experimentation.

Sailing Ship Hydrodynamics Analyzed and Compared with Eighteenth-Century Ideas

In hindsight, how did the various concepts of fluid flow and the resistance of sailing ships compare with current knowledge? Modern ship hydrodynamics is based on the work by William Froude from the 1870s, though greatly expanded through experimentation and finite-element analysis. In Froude’s formulation (still used today), total resistance is due to two factors that can be treated independently.

Pressure forces Pressure increases at the bow, raising the water surface and creating a bow wave system. It decreases along the length of the ship, creating another wave system near the stern. The wave systems take energy away from the hull, and interactions between them causes resistance not to rise uniformly with speed, but to have various humps and hollows. Pressure forces are the most sensitive to hull shape.

Viscosity A large part of viscous resistance—the friction between internal layers of a fluid—derives from the friction of the water with the skin of the ship. This can be approximated by assuming that the frictional resistance per unit area of a ship’s hull is the same as that of a submerged flat plate of similar length and surface finish. Skin friction is very dependent on the roughness of the surface; barnacles add considerably to the drag. But ships are not flat plates, and the shape of the ship contributes several other components to viscous resistance, often lumped under the terms “viscous pressure resistance” or “form drag”: separation, eddymaking, and viscous wavemaking drag. The flow of water begins to separate from the hull right at the bow, creating an increasingly thick boundary layer along the hull that carries its own drag due to loss of momentum. The unevenness of the hull causes the flow to break away, forming eddies that contribute even more drag. Finally, the viscosity changes the pressure

distribution, resulting in higher wavemaking resistance than for an ideal fluid. Friction is almost insensitive to hull shape; viscous pressure resistance can be sensitive to hull shape, but in a complex way.¹⁴⁶

The vast majority of the resistance of an eighteenth-century sailing ship was due to viscosity. As figure 3.29 shows, tests conducted in 1937 on a model of the British 104-gun HMS *Victory* showed that wavemaking resistance was significant only above about 10 knots. Records of maximum speeds for ships of that era are somewhat unreliable, but they indicate that larger ships could attain 11 to 12 knots in a strong wind. However, they must have spent most of their service at speeds well below that, so for these purposes, wavemaking resistance can be discounted. Skin friction, therefore, was clearly the dominant factor for most sailing ships, with some additional influence due to viscous pressure resistance.¹⁴⁷

It should be noted that the scaling factors for the models of that time were often, by chance, near to the real-ship scale. Since the time of Froude, similitude between model and real ship has been expressed in a nondimensional form called the Froude number:

$$\frac{v}{\sqrt{gL}}$$

where: v = velocity, g = gravity acceleration, and L = length on waterline.

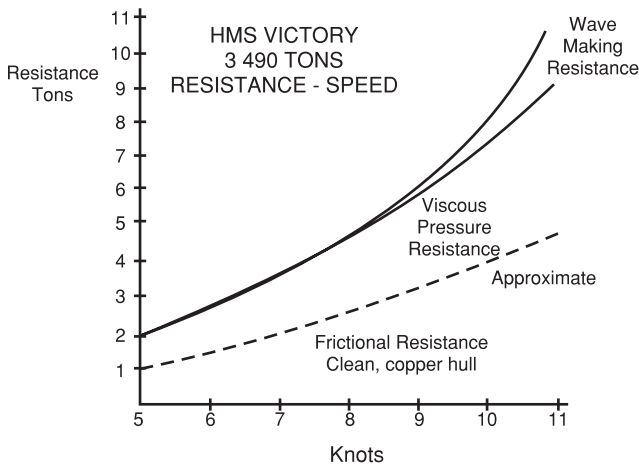


Figure 3.29

Resistance components for model tests of HMS *Victory*. (After Brown, "The Speed of Sailing Warships" [1990], p. 189)

Warships of that era were between 45 and 55 meters in length and had a typical speed range of 6–12 knots (3–6 meters/second), giving them a Froude number of 0.13 to 0.28. Bossut's models, for example, were around 2 meters long and were towed between 0.5 and 1.4 meters/second, giving them Froude numbers of 0.11 to 0.3. Therefore, the results the experiments obtained would, notionally, be applicable to actual ships.

Looking at the experimental results with this current knowledge, it is ironic that Chapman's theories of stern shape, although he regarded them as failures, were probably the most relevant to real ships, as stern shape affects both the shape of the boundary layer and eddymaking resistance. The observations of Borda, Thévenard, and Bossut regarding the influence of waves on resistance were probably correct at the higher speeds, but they were unable to determine either the reasons or the effects. Du Buat and Romme both suspected pressure as a principal element of resistance, which, though true, was far less important than viscous effects. In this, Du Buat was the closest to identifying skin friction as the most important factor (and Bossut the most spectacularly wrong by stating that it would "disappear" compared with bow shock). However, Du Buat's hydraulic results led him to neglect hull roughness, even when every sailor knew that fouling (growth of barnacles and seaweed on the hull) greatly reduced a ship's speed. In fact, hull roughness would be identified as a principal factor in Anglo-French sailing trials conducted in the 1830s (discussed later in this chapter).

Is There Evidence That French Ships Were Faster Because of Theoretical Efforts?

Part of the reason for the formation of the British Society for the Improvement of Naval Architecture in 1791 (discussed in chapter 6) was the perception that French ships were better and faster than British ones. Sewell and others attributed French superiority to the application of hydrodynamic theory by the French constructors, which, as described earlier, actually consisted of their calculating a "ratio of bow resistance"; the experimental results of Bossut and others never found their way into actual ship designs. This perception was reinforced by the reports of British navy captains who, some later authors would suggest, were eager to increase the prize valuation they received for capturing enemy warships, and thus would exaggerate the speed advantage of the captured ships. The Navy Board was so convinced of this superiority that in the 1780s, they authorized a number of 74-gun ships to be built from the lines of captured French warships; in this they were supported by a growing number of sea officers who believed that the French "ideal" of scientific ship design led to faster ships.¹⁴⁸ This naturally invites the question, If French warships were indeed faster, how were they captured in the first place?

The speed of a sailing warship of the eighteenth century was dependent on a number of factors, of which hull shape, affecting primarily wavemaking resistance, was probably one of the least important. By far the most important was the skill of the commander and his crew in choosing the right headings, the speed of maneuvers and in furling and unfurling sails, and of course ensuring the upkeep of the ship. In the eighteenth century, British navy ships were often at sea for much longer periods than French ships, and crews generally trained more extensively. This helps explain why the British navy captured far more ships than any other navy in that century—over five times as many as the French navy in terms of displacement tonnage.¹⁴⁹

The material condition of the ship was also important. The sail plan and rigging influenced the most effective speed and heading, and sailcloth could be heavier or lighter, depending on wind conditions. The ballasting, *dérive*, and stability of the ship affected the underwater hull shape; as it became asymmetrical under trim, yaw, and heel, the resulting vertical and sideways forces added to the drag. Finally, the smoothness of the hull was a critical factor.

It is unwise to dismiss out of hand the anecdotal reports that eighteenth-century French warships were faster than their British counterparts, which were made by British officers who were generally quite learned and very astute, and were later repeated by John Sewell and members of the Navy Board. However, without direct side-by-side evidence, it is difficult to verify this claim. A statistical analysis of ship chases during the French Revolution and Napoleonic Wars (1792–1815) was made by the British historians David K. Brown and Phillip Pugh to determine whether the historical data yielded any clues.¹⁵⁰ To highlight the effect of the quality of seamanship on performance, they divided the chases into three groups:

Faster	Slower	Number of Chases
British built/manned	French built/manned	40
French built/British manned	French built/manned	8
French built/manned	British built/manned	6

French built/British manned ships were those that had been captured as prizes by the British navy during the wars, a common occurrence. A visual representation of the data was arranged to show speeds in arbitrary units according to a Gaussian distribution (figure 3.30).

The figure shows that for all British-manned ships, French-built hulls performed marginally better than British-built hulls, which lends some credence to Sewell’s claims and British Navy Board beliefs. It is possible that French constructors, in comparing their “ratio of bow resistance” with those of other ships of known qualities,

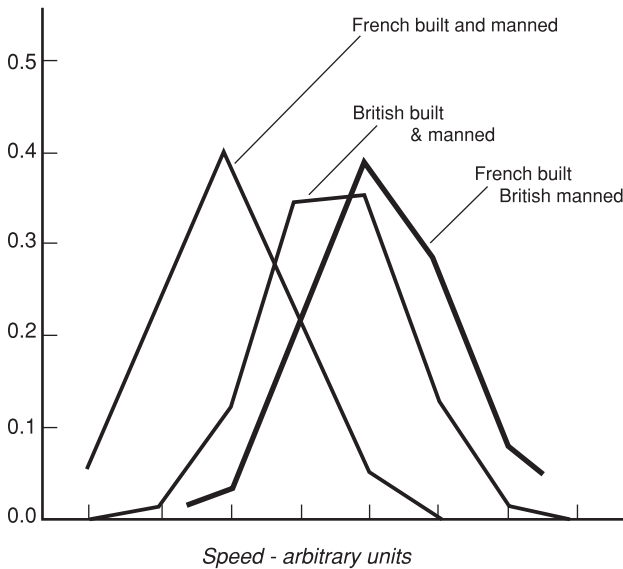


Figure 3.30

Relative speeds of French and British warships (1793–1815). (After Brown, “The Speed of Sailing Warships” [1990], p. 180)

consciously created hull shapes derived from those that had already demonstrated superior speed. But it is doubtful that this hydrodynamic insight was any more effective than simply modeling new hull lines based on previous successes. In any event, given that the majority of ship resistance was due to viscous effects unrelated to hull form, the contribution of any improved bow shape would have been small, and probably overshadowed by other factors such as lading and rigging.

What Was the Effect of Technology and Shipbuilding Practice on Ship Speed?

The more remarkable result of the Brown/Pugh study was that French-built hulls performed much better in British hands than in French ones. Was this in fact due to British seamanship, or to British technology and shipbuilding practice? One answer may be found in the report of a French commission tasked to investigate the results of the side-by-side Anglo-French sailing trials of 1832. Ironically, these trials, jointly organized by the British admiral Pulteney Malcolm and the French admiral Alexandre Louis Ducrest de Villeneuve (enemies at the time of the battle of Trafalgar), were conducted off the coast of Sussex in recognition of the superiority of the *British* fleet over the French fleet in matters of speed and maneuvering. According to the British

naval constructor and historian John Fincham, the French navy was so disappointed with the performance of its ships that it established a commission to compare French and British construction in detail, the results of which he quoted at length.¹⁵¹ The commission noted that French-built hulls performed better in British hands due to extensive modifications to the hull and rigging; unfortunately, they were silent on the subject of crew quality and seamanship. They pointed to the 74-gun *Hoche*, designed by the renowned French constructor Jacques-Noël Sané, captured in 1798 and refitted as the HMS *Donegal* under Pulteney's command, which later sailed in the joint squadron:

It has often appeared that the best sailers [of the British] have been found to be of French origin. . . . they have obtained this result of sailing particularly in our old frigates, by lightening their armament, reducing the length of their masts, diminishing proportionally their ballast, and increasing, in a remarkable manner, the depth of their false keel.¹⁵²

In other words, the better performance of the captured French ships had little or nothing to do with the hydrodynamic shaping of the hull; the commission found that there was almost no real difference in hull forms compared with British ships. Rather, they believed that performance differences were due primarily to the way ships were rigged and fitted out.

Skepticism Sets In

In spite of popular (and even professional) opinion that French science somehow made French ships "better," British constructors had every right to be skeptical of the benefit of the hydrodynamic theories developed in France. As early as 1748, the influential British engineer Benjamin Robins stated in a letter to the French mathematician Pierre-Charles Le Monnier that he took "no notice" of the resistance theories of Bouguer and others.¹⁵³ Bouguer's work on resistance became well known in Britain thanks to a reasonably faithful translation of excerpts from both *Traité du navire* and *Éléments de l'architecture navale*, published in *Treatise on Ship-building and Navigation* by Mungo Murray, a British constructor at Deptford, in 1754 and 1765. Murray was rather skeptical of the process, warning that "the particular form of a ship cannot be determined by rules that will admit of a mathematical demonstration."¹⁵⁴

In France, the "ratio of bow resistance" calculation disappeared from ships' plans after 1782. After a series of problems with the fleet, Charles-Eugène de la Croix de Castries, minister of the navy since 1780, had appointed Jean-Charles de Borda to develop a standardized set of designs for navy ships with the constructor Jacques-Noël Sané (described further in chapter 6). Borda's own experience with hydrodynamic theory and practice from his 1767 experiments convinced him that the underlying theory

was, as previously stated, “useless and even dangerous.” Even though the 1765 ordinance was still theoretically in effect, Borda in practice suppressed the calculation of the ratio of bow resistance.

Probably the most damning commentary on the underlying hydrodynamics came from the Spanish constructor Jorge Juan y Santacilia. He was one of the few theoreticians who actually designed and built ships, so he was in a position to evaluate the utility of ship theory. Juan was asked by his colleague José Romero Fernández de Landa to explain French design methods, now that the constructor Jean-François Gautier, brought from France in 1765 by Minister of State Jerónimo Grimaldi to help consolidate the French and Spanish fleets, was beginning to take control of Spanish naval construction. In a 1766 letter generally critical of theoretical naval architecture (alluded to in chapter 1), Juan y Santacilia wrote:

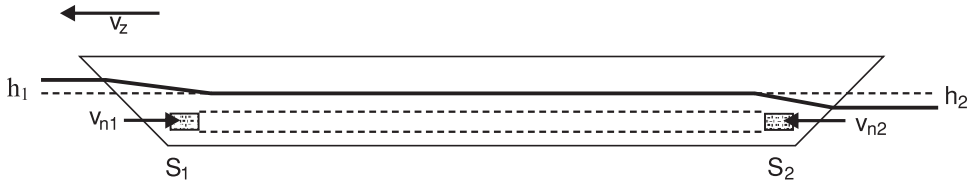
... all the other [theories] are false; the resistance of water against the bow is not what [Bouguer and Duhamel] deduce. ... It would be very lengthy to explain; the fact that I have spent more than ten years on this subject tells you how extensive it is.

Your difficulty over the relation between the form of the Bow and Stern is understandable and the rules given by Duhamel are not even practical and just superfluous. What I can tell you is that the form of the bow must, for many reasons, be more full than the stern; by how much may be deduced from the requirements or destinations of the Ship; one that is fuller may be good for one thing and bad for another, and vice-versa.¹⁵⁵

Juan y Santacilia's skepticism appears to have taken a firm hold in the Spanish navy. Even with Gautier in charge of construction, no ship plans contained calculations of the ratio of bow resistance. A rather lengthy examination of ways to increase a ship's speed, conducted in 1781, looked at practical measures such as lengthening the ship, decreasing the beam, and reducing weight, but made no mention of hydrodynamic theory.¹⁵⁶

New Ideas in Ship Resistance Theory

Although Juan y Santacilia was contemptuous of the usefulness of hydrodynamic theory in ship design, he continued to contribute to its advancement. In his great work *Examen marítimo, teórico práctico* (Maritime Examination, Theoretical and Practical) he pointed out several faults in the ship resistance theories of Bouguer and Euler, and sought to correct them. He argued that the fluid at the stern had to fill in the void left by the passing ship, and would exert a force on the hull that would push the ship forward.¹⁵⁷ As shown in figure 3.31, taking an elemental area S at the bow and stern (shaded areas), connected through the ship as if by a tube, the difference in force would be

**Figure 3.31**

Effects of bow/stern pressure and change in surface levels according to Juan y Santacilia (1771). (After Simón Calero, “La mecánica de los fluidos en Jorge Juan” [2001], p. 244)

$$DF = \frac{1}{2} \rho (v_z \pm v_n)^2 dS,$$

where: dF = differential force, dS = surface element, v_z = velocity of ship, and v_n = normal velocity of fluid at element S (1 = bow, 2 = stern).

The “+” inside the parentheses indicates velocity at the bow; the “−”, velocity at the stern.

According to Juan, the increase in pressure at the bow would raise the surface of the water at the differential element

$$h_1 = \frac{v_{n1}^2}{2g}$$

and cause an equivalent decrease in the surface of the water at the stern (which in fact double accounts for the change in pressure). Substituting $v_n = v \sin \theta$ (where θ is the angle of the vector normal to element), then expanding and discarding the insignificant elements, the equation became

$$dF = \rho \sqrt{(2gh)} v (\sin \theta_1 + \sin \theta_2) dS.$$

Although Juan never used the word “pressure,” the result was not much different from the experimental observations on pressure of Du Buat and Romme. Juan’s calculations showed that the difference between his complete derivation and that of Bouguer was minor. Nonetheless, the complete derivation became a part of the curriculum of the French School of Student Engineer-Constructors of the Navy after 1783, when *Examen marítimo* was translated into French by the hydrographer Pierre Lévêque; Juan’s derivation was also the basis for the entry “Fluids, Resistance of” in the colossal *Encyclopédie méthodique: Marine*.¹⁵⁸ However, by that time French constructors were no longer calculating hull resistance as part of the design process, so it became simply an academic exercise.

Leonhard Euler, in his last paper on rational fluid mechanics, “Essai d’une théorie de la résistance qu’éprouve la proue d’un vaisseau dans son mouvement” (Attempt at a Theory of Resistance Encountered by the Bow of a Vessel in Its Motion), written in 1778, attempted to reconcile a purely theoretical approach with the experimental results of Bossut and Coulomb. Simultaneously with and similar to Du Buat, Euler proposed dividing ship resistance into separate components: bow shock, hydrostatic pressure, and friction. Although he provided definite integrals to calculate the first two effects, he admitted that friction could only be estimated empirically, and suggested a mechanism to estimate this force.¹⁵⁹

In some cases, the results of the various experiments were used to support particular ideas about ship construction, regardless of whether they had any bearing on them. Charles-Louis, marquis of Ducrest, was a tireless self-promoter of his capabilities as a soldier, politician, administrator, hydraulic engineer, and constructor, although he was most famous at the time for being the brother of Stéphanie Félicité Ducrest, countess of Genlis, an author of romance novels favored by Napoleon. In his 1777 book *Essais sur les machines hydrauliques* (Trials on Hydraulic Machines), he extensively cited the experiments of Borda and Thévenard to support his proposal of a hull with an elliptical cross section, although neither of the experimenters ever recommended that particular hull form.¹⁶⁰ This concept was short-lived, for while Ducrest was in exile from the French Revolution in Denmark in 1799, he convinced a wealthy Danish shipping magnate and counselor to the king, Frédéric de Coninck, to finance a 500-tonne ship based on his ideas. In his *Nouvelle Théorie de la construction des vaisseaux* (New Theory on the Construction of Vessels), Ducrest cited the results of Romme, Borda, and Thévenard, then reprised Hoste’s assumption (without naming him) that, in effect, resistance was proportional to the mass of the water the ship displaces as it moves forward.¹⁶¹ He invoked these authorities (though without showing how they applied) to support his concept of a ship built of lightweight pine boards, with straight sides and a maximum section very far forward. He conducted many trials on the ship, presumptuously named *Svar-til-alt* (Answer-to-Everything), and claimed success in its speed and construction cost—not surprising, given its very light construction—although the trials were disappointing.¹⁶²

Citing authorities to support weak ideas was not only the realm of amateurs like Ducrest. The well-regarded French constructor Pierre de Gay, in his 1792 *Mémoire sur la forme de la carène des vaisseaux* (Memoir on the Hull Form of Vessels), also used the results developed by Romme on pressure at the fore and aft ends of the ship to insist that giving the bow and the stern an equal, convex shape would yield the least resistance. Gay, who wrote many of the long, theory-laden articles in the *Encyclopédie*

méthodique: Marine, inexplicably refused to provide any analytic proof in his memoir, stating, “I don’t give any algebraic formulas, because it would require showing these applications that would lengthen this memoir.”¹⁶³

Ironically, it was in part the misplaced fear of superior French hydrodynamics that would lead to the real breakthroughs in resistance theory. The Society for the Improvement of Naval Architecture, soon after its creation in 1791, set out one of its principal aims as “ascertaining the laws of resistance of water,” for which it offered a prize of £100 (around \$16,000 in 2002), similar to the prize for model ship trials the Society for the Encouragement of Arts, Manufacture and Commerce had offered in 1758.

Mark Beaufoy, a wealthy brewer’s son and more than just an amateur scientist, was a member of Sewell’s Society. He took up the challenge in 1793 when William Wells, a member of the Society and owner of the Greenland Dock (a huge whaling ship dock in Rotherhithe, just northwest of Greenwich) allowed him free use of his dock. Beaufoy, principally using his own money, conducted a methodical series of 1,671 recorded trials of various geometrical and ship shapes from 1793 to 1798. Although he used the same falling-weight motive power as previous experimenters, Beaufoy introduced a number of innovations, including an automatic velocity recorder. By this time, the separation of resistance into components was becoming widely accepted, and Beaufoy (on the advice of Charles, third earl of Stanhope) defined them as

- Plus pressure at the bow
- Minus pressure at the stern
- Friction.

A careful reading of Beaufoy’s works shows that by “pressure” he really meant “force,” but Beaufoy did not consider it to be a source of wavemaking. He towed bodies both at and below the surface to establish the effects of end shapes on pressure, and towed thin planks (i.e., effectively without pressure-causing end shapes) to determine laws of frictional resistance. Beaufoy published his results with the Society in 1794 and 1800, although it would not be until 1834 that his son (also named Mark) fully tabulated them. This publication coincided with the coming of the steam engine, and in 1809 Robert Fulton used Beaufoy’s 1800 report to the Society to estimate the sizes of engines and paddles required for his steamships. In 1840, the British civil engineer Isambard Kingdom Brunel used Beaufoy’s work as a benchmark for his studies of the screw propeller of *Archimedes*, prior to fitting it on the new iron steamship *Great Britain*, and twenty years later the British merchant ship constructor John Scott Russell cited Beaufoy in the design of *Great Eastern* and of packet ships.¹⁶⁴

By the 1820s, various methods of calculating resistance were employed, most often using ratios from full-scale tests. The most famous example of this was the Admiralty coefficient (or constant) used by British merchant and naval constructors; but even this much later formulation still had echoes of Newton's ideas of shock theory, as it continued to use the midship area in calculating resistance.¹⁶⁵ The attempts at a general theory of fluid resistance gave way to independent, practical estimates for powering of steamships. This trend would continue until William Froude developed his experimental methods in the 1870s, which gave accurate, general results that could be used across a wide range of ship types.

The Solid That Would Not Die

The solid of least resistance continued to capture the imagination long after experimental and theoretical developments should have killed it off. The Society for the Improvement of Naval Architecture published a short paper by the mathematician William Emerson that gave a table of coordinates for a bow of least resistance, based on his own *Doctrine of Fluxions*.¹⁶⁶ In 1808, the Swedish mathematician Gustaf Gabriel Hällström published a paper in the *Proceedings of the Swedish Academy of Sciences* that explained how to derive a bow of least resistance based on recent work on fluid resistance by his fellow mathematician Zacharias Nordmark. Hällström developed a complex set of equations, followed by a table of offsets, that showed a sharp, lens-shaped hull much different from either Newton's blunt solid or Bouguer's parabolic surface.¹⁶⁷ In 1810, George Cayley, a British amateur engineer who was one of the first to write extensively about the mechanics of flight, suggested that Newton's solid of least resistance was the most apt form for an aerial body.¹⁶⁸

The idea of such a solid as a ship form resurfaced in the mind of John Scott Russell around 1834, although it bore no resemblance to any previous work. Russell, a private British shipbuilder who carried out projects for canal boat companies and packet lines (and later, more famously for Isambard Kingdom Brunel), had conducted model tests aimed at finding a relationship between maximum cross section and resistance. He noted a consistent drop in resistance at specific speeds, which varied depending on the shape of the bow. Russell set out to find the equation of a two-dimensional waterline curve that would produce the least resistance. His mathematics was obscure, but he evidently conceived a parabolic form that would create the least transverse acceleration of water particles when moving forward. The concept eventually became his "waveline principle" of waterlines, which he used in developing the hull form for the passenger ship *Great Eastern*, built in 1859.¹⁶⁹

Perhaps no one better personified the intellectual and emotional attraction of the solid of least resistance than the American statesman and polymath Thomas Jefferson. Originally a farmer by trade, Jefferson sought to create a more efficient plow than those with the traditional moldboards. Robert Patterson, a professor of mathematics at the University of Pennsylvania, reminded Jefferson of William Emerson's solid of least resistance. Jefferson went on to create a wedge-shaped moldboard, which he proudly wrote about while vice president of the United States.¹⁷⁰

The most poignant evocation of the solid of least resistance may be Jefferson's famous letter to Maria Cosway, a married British artist whom he met in Paris while serving as U.S. ambassador to France. In his "Dialogue Between My Head and My Heart," Jefferson expressed his longing for her, set against her (and his) unavailability, as an argument between emotion and reason:

Heart to Head: "When nature assigned us the same habitation, she gave us over it a divided empire. To you she allotted the field of science, to me that of morals. When the circle is to be squared, or the orbit of a comet to be traced; when the arch of greatest strength or *the solid of least resistance* is to be investigated, take you the problem: it is yours: nature has given me no cognizance of it. In like manner in denying to you the feelings of sympathy, of benevolence, of gratitude, of justice, of love, of friendship, she has excluded you from their control. To these she has adapted the mechanism of the heart."¹⁷¹

Jefferson wrote the letter on 12 October 1786, the evening after Maria Cosway left Paris. He never sent it, and they never saw one another again. In the end, he could not resolve the conflict between his desire to hold on to the woman he idolized, and his intellect, which told him that she could never be part of his future in the United States. It is perhaps this desire to hold to an ideal, even when reason shows that it has no future, that explains why the solid of least resistance continued to be the touchstone of hydrodynamics for so long.

4 Inventing the Metacenter

The stability calculation is the global stock in trade of modern naval architects. It is invariably the first course taught in the naval architecture curriculum, and is one of the most closely monitored elements of ship design. The equation for the metacenter—the initial measure of ship stability—is easily the most recognizable equation in the profession, attaining for a brief period the status of icon for the Swedish Fleets Constructor Corps (figure 4.1). However, the *ability* to calculate ship stability did not arise from the *need* to do so; rather, the reverse is true.

The metacenter fairly burst upon the scene in the 1730s. It was not developed in response to stability accidents; these were actually rare compared with other accidents that routinely befell ships at sea. It was not the crescendo of a concerted effort by academicians working on naval science; they were engaged elsewhere in problems of navigation, maneuvering, and resistance. The elements necessary for a comprehensive theory of ship stability took two millennia to put into place. Even then, there were several obstacles to a practical knowledge and acceptance of the theory, such as the emphasis on measuring cargo capacity instead of displacement, and developing means to accurately calculate displacement. Not the least of these obstacles was recognizing that there was a “stability problem” in the first place.

Stability Accidents

9 November 1664: The seas were calm that Sunday morning, though that would have brought little comfort to Captain Verdille, commander of *Lune*. Returning from a failed campaign to capture and establish an outpost in Djidjelli, a small town in present-day Algeria, he had been about to enter Toulon, only to find that the French port was under quarantine because of an outbreak of bubonic plague. The duke of Beaufort, commodore of the squadron, had given the order to move the ships to the Îles d'Hyères, a small group of islands 12 nautical miles outside Toulon harbor, to ride out



Figure 4.1

The metacenter as icon: Swedish Fleets Constructor Corps uniform button (1793). (D.G. Harris, *F.H. Chapman* [1989], p. 156). Credit: Conway Maritime Press.

the quarantine. Verdille, 80 years old but still sharp, had refused to weigh anchor. *Lune*, a 54-gun ship of about 800 tonnes, had been taking on water for a month and was increasingly sluggish at the helm. It had been constructed 23 years earlier in Brest to be the pride of Richelieu's fleet, but it was beginning to come apart.

Beaufort had ordered Gideon (Gédéon) Rodolphe, the Dutch constructor in charge of the Toulon dockyard, to inspect the ship. Although seams were opened up, which normally would require that the planks be removed and refitted, Rodolphe simply had them recaulked and pronounced the ship "safe for all oceans." At the last minute, from 400 to 600 men of the 1st Regiment of Picardy came aboard to be transferred to the Îles d'Hyères, further overloading the ship. Verdille, originally from Malta, where children were practically raised in the water, was one of the few on board who could swim. Most sailors did not—it merely prolonged the agony of drowning.

Now, *Lune* was half an hour out of harbor and heading southeast, with lower gun ports closed and officers continually checking the bilges for leaks, when the hull made a cracking sound like cannon firing. Frames and planking split apart just forward of the mainmast, bringing in torrents of water. Masts and rigging broke and fell under the press of sail, and cannon tumbled into the disintegrating hull. The ship went down by the head "like a marble." Verdille was one of only 60 men who swam the 2 miles to shore; with between 540 and 1,120 deaths, the wreck was responsible for one of France's greatest maritime losses of life.¹

The story of the shipwreck quickly became distorted. Although the foundering was due to structural failure, the perception was that it had been due to poor stability and open gun ports. The French mathematician Paul Hoste, writing 30 years later in *Théorie de la construction des vaisseaux* (Theory of the Construction of Vessels), would use the foundering of *Lune* to introduce his theories of ship stability, stating, “There is no greater fault than a vessel which cannot carry sail.”² Hoste may have resorted to the *Lune* because it was comparatively fresh and still painful in the minds of the French Admiralty. There were other examples as well.

On 19 July 1545, the British 37-gun *Mary Rose* capsized and sank just outside Portsmouth, on the south coast of Britain, while engaging a French fleet during Henry VIII’s war with Francis I. It had just fired one broadside and was coming about to bring its other broadside into action when it heeled over alarmingly. Its open gun ports admitted water, and it capsized with over 500 men, in full view of Henry and his court. It is doubtful that an inherent lack of stability was to blame. The ship was by then 35 years old, and had seen many engagements and worse weather; but it had grown heavier over the years and had also recently undergone a major overhaul during which it was fitted with heavy cannon and gun ports were cut into the hull, dramatically lowering its available freeboard. The capsize was probably due to a combination of inexperience with these gun ports, mishandling of the sails, and being overloaded with soldiers; however, no board of inquiry was ever called to establish the reason.³

Vasa had been the proud flagship of King Gustavus II Adolphus of the Vasa dynasty of Sweden, central to his plans to make the Baltic a Swedish lake. The principal constructor at the Royal Dockyards in Stockholm, Henrik Hybertsson of the Netherlands, had already successfully built several warships under contract for the Swedish navy, so *Vasa* should have been a fairly straightforward project. However, Hybertsson died early in the construction, so *Vasa* was finished by another constructor. On 10 August 1628, in Stockholm harbor’s calm waters and less than half an hour after it left the wharf, a gust of wind caught the ship and heeled it slightly to port; it briefly righted and then heeled over again, this time submerging its open gun ports. Water gushed in, and the ship foundered under full sails, losing 50 men in the process. The subsequent inquiry failed to assign any blame; however, the court suspected that *Vasa* was designed with too little room in its hold for ballast, and all but accused Klas Fleming, the vice admiral in charge of the construction, of rushing the ship into service and blatantly ignoring the results of a crude stability test that showed it to be very unstable.⁴

Of these accidents, only one—*Vasa*—could be classified today as due to flawed stability, and even that conclusion is now being called into question.⁵ At the time,

however, all were *thought of* as being stability accidents, and they all resulted in the loss of a nation's major warship, some with horrific loss of life—yet none of the accidents provoked any action to solve the “stability problem.” The reason appears to be that a “stability problem,” in the sense of a deficit or flaw in the current state of knowledge that required a concerted action to solve, simply did not exist in the eyes of either admiralties or academicians. The best example of a “problem” that provoked a concerted action to solve it was that of navigation.

The British naval historian Nicholas A. M. Rodger, in *The Wooden World*, takes a comprehensive look at the dangers of seafaring. Although he discusses fire, weather, and enemy action, he zeroes in on navigational faults as presenting the greatest hazards, including being driven up on unexpected shores, grounding on unknown shoals, or simply being lost without a trace.⁶ Even in wartime, between 50 and 60 percent of British warships were lost due to foundering as a result of various types of navigational accidents, the most notorious of which was an incident in 1707, when an error in estimating longitude put four British warships onto the rocks of the Scilly Isles and killed over 1,600 men.⁷ In one not-unusual eight-year period (1775–1782), 65 British navy ships foundered, wrecked, or disappeared.⁸

Governments of all nations, especially their admiralties, invested huge amounts of resources to solve the “navigation problem”: schools of navigation and hydrography were established long before any schools for constructors; navigational texts were published in far greater numbers than shipbuilding treatises; and observatories were established to improve celestial fixes. France, Britain, and Spain financed costly expeditions—such as the Geodesic Mission to Peru—to establish the correct variation of latitude, and offered large prizes for the accurate calculation of longitude, notably the famed prize under the 1714 Longitude Act, provoked by the 1707 disaster in the Scilly Isles, which offered £20,000 (about \$3.2 million today) and was eventually won by John Harrison for his marine chronometer.⁹

Sailing ships were very much at the mercy of the wind. They could suffer knockdowns from strong gusts, or be mishandled during a maneuver and blown over onto the side. In one famous incident, the Swedish 124-gun *Kronan* suffered a knockdown in battle on 1 June 1676 due to a strong wind gust combined with too much sail. After it had been lying on its side for some minutes, the ammunition magazine detonated and the ship sank.¹⁰ It was often difficult to distinguish between accidents due to poor stability and those due to poor seamanship (such was the case with the *Mary Rose*). It was in fact rare to find true “stability accidents” such as the one that may have befallen *Vasa*. One reason is that the basic rules of thumb that provided good stability—proportions of beam and depth, quantity of ballast—had been developed over cen-

turies by constructors. To be somewhat simplistic, good stability was usually a matter of adding the proper amount of ballast, and poor stability was corrected by adding more ballast. If the situation was particularly bad—if the ship was “crank” or “tender” (meaning, respectively, it rolled too much or stayed heeled over for long periods), or if a warship’s gun ports were too close to the water for more ballast to be added—then the hull was “doubled” or “girdled,” that is, a second layer of wood planking was added to the outside of the hull (usually just above and below the waterline); sometimes a third layer was nailed on. The origins of this procedure are unknown, but probably go back centuries. It worked, but no one understood exactly why.

Even experienced constructors would resort to this postconstruction fix; William Burrell, general surveyor of the East India Company, had to girdle ten warships he built between 1619 and 1623.¹¹ Paul Hoste complained in his 1697 treatise, “Most vessels must be girdled (*soufflage*; literally, “inflating”) but that makes the vessels heavier and a worse sailer, plus it is very expensive. . . . it would seem easy for shipwrights to give vessels in the original form that which they would have had after doubling, but that makes them worse sailers.”¹²

Although Hoste devoted 20 pages of his treatise to ship stability, he was almost the only mathematician or scientist to do so until Pierre Bouguer and Leonhard Euler. As has been shown, the first ship theory problem to be identified, investigated, and debated by academics involved the *dérive*, and was followed by investigations into resistance, admeasurement, and masting of ships. Even Bouguer, when first describing to Maurepas his plans for research into ship theory, spoke of masting and “the laws observed by fluids in their shocks,” but said not one word concerning ship stability.¹³

For these reasons—poor stability was generally corrected by time-tested means, and stability accidents themselves were relatively uncommon—there was no concerted effort by naval officers, government officials, and scientists to solve the “stability problem” in the way they tackled the “navigation problem.”

Tons or Tuns?

The natural emphasis by shipowners to measure ships by their cargo-carrying capacity, rather than by their displacement, added to the difficulty of developing a practical means of measuring a ship’s stability, which depended on a reasonably accurate calculation of displacement. On the other hand, the accurate calculation of the cargo-carrying capacity of a ship, called *admeasurement*, was of no practical value to constructors as a design and construction tool until the nineteenth century, when mechanical means of measuring areas and volumes were perfected.¹⁴ Absent those

tools, a constructor could not directly translate a requirement to carry a specific cargo into a ship design, except by experience. Ship owners, however, needed a means of quickly establishing the cargo capacity (earning potential) of their ships, and comparing it with others. The simplest way to do this was by counting the cargo directly, either pieces of cargo or cargo containers.¹⁵

But ships would carry an enormous variety of cargo (wine, beer, fish, coal, grain, wood, etc.) that would be transported in different types of containers (bushels, barrels, crates, etc.) of varying sizes and capacities. In Hanseatic northern Europe, a principal cargo was grain, and a set number of bushels constituted a *last* (about 2,000 kilograms). Farther south, wine was one of the most traded commodities. In Italy and on the Adriatic, it was carried in *botta* of about 750 liters, while in Spain it was in *pipas* of 513 liters. In France, wine barrels came in five different sizes. On the Bordeaux-to-Britain route, wine was a very profitable commodity, since Aquitaine had been part of Britain until 1373 and still accounted for almost all its wine. The Bordeaux wine barrel was called in French *tonneau* or *tonne*, and in English, *ton* or (more commonly) *tun*. Over time, the *last* and the *tun* became the most common units of measure for both weight and volume, an often confusing practice that persists to this day—“deadweight ton” is a unit of cargo weight, and “registered ton” is a unit of volume (as I note in the preface, to avoid this confusion, I will hereafter use “ton” for weight and “tun” for volume). In the case of the tun, the shape of a barrel varied from cooper to cooper, so there was often great uncertainty as to the actual amount of wine it contained.¹⁶

In Britain, to avoid this problem of disparate barrel capacities, the tun became codified in 1423, under Henry V, as not less than 252 gallons.¹⁷ This was done to control the collection of import duties, called “tunnage.” Customhouse officials, like ship owners, determined cargo capacity by counting barrels and then levied the appropriate tax. As ships grew larger, this process became onerous and prone to fraud, since officials were reluctant to pull out and hand-count every barrel. There was an increasing need to introduce some standard form of admeasurement that did not rely on barrel-counting, in order to tighten up on fraudulent practices as well as to have a common unit that could tell officials the cargo capacity of a ship, regardless of the type of cargo it carried.¹⁸

Admeasurement based directly on ship dimensions sprang up simultaneously in several places during the late 1500s, although Venetian shipowners had, since the 1300s, been using formulas such as $(\text{keel} \cdot \text{length} \times \text{beam} \times \text{depth})/30$ to obtain a ship's capacity in *botti*.¹⁹ Right from the start, these methods were often employed to compute cargo capacity in both weight and volume terms, using the same units. The

constructor Mathew Baker developed the first British rule for measuring tunnage based on a ship's principal dimensions. In a 1582 manuscript on the subject, he dealt with the calculation of the stowage of victuals for both merchant and naval ships, which originally appeared in his earlier *Fragments of Ancient English Shipwrihty* as sectional area computations to "know the tunnage of a ship."²⁰ Starting with a ship whose actual hold capacity or tunnage (i.e., the number of barrels or amount of other cargo carried) was known from direct admeasurement, it would be possible to estimate the tunnage of a second ship using the ratio of their "cubical numbers" (length $\times$ beam $\times$ depth). To simplify the comparison, Baker divided the cubical number by 100. He called the resulting cargo volume "tuns," and to get the equivalent cargo weight (which he called "dead weight or tonnage"), he added 1/3 more. For example, he calculated that the London cargo ship *Ascension* carried 160 tuns (volume) but 213 tons (weight) of cargo.²¹ There was no attempt to translate units of volume into weight, just a rough-and-ready conversion.

Although the "tuns and tonnage" system was devised for merchant vessels, the British navy also adopted it as a means of describing its ships. By 1592 the navy was calculating tunnage by "direct rule" (later known as "Mr. Baker's old rule"), that is, not admeasuring ships by comparison, but directly, by using the cubical number with a divisor. The divisor, originally 100 for convenience, was changed several times before it was fixed by Parliament at 94.²²

On the north coast of Spain, the constructor Cristóbal de Barros published the first Spanish regulation on admeasurement in 1590, to take the place of measurements in use from as far back as Columbus. In Barros's formula, the tunnage in *toneladas* (8 cubic *codos* or cubits of 56 centimeters each) was given by $(length \times beam \times depth/2) \div 8$. Another 20 percent was added to the tunnage calculation for naval ships, to account for the fact that the first deck, ostensibly unused on merchant ships, was taken up with armament. This formula was revised in 1613, with the 20 percent addition to tunnage for naval ships now extended to merchant ships, this time (confusingly) to account for unmeasured volume at the fore and aft ends. Tunnage formulas were revised several times before settling into a stable form that would last until 1830.²³

Nikola Sagroević, a hydrographer and ship captain from Ragusa (now Dubrovnik), developed a complex system of admeasurement in the late 1500s. In his now-lost manuscript "Il carteggiatore" (The Cartographer), he divided the ship into three sections—forward, middle, and aft—and carefully measured each to accurately admeasure the total volume and tunnage.²⁴ A similar system was developed in 1661 by another Ragusan, Petar Damjan Ohmućević, a mathematics teacher who worked in the shipyards of Gru.²⁵ Neither work was published, nor is there any indication of their

widespread use, perhaps because their systems were more complex than the widely used length $\times$ beam $\times$ depth rules.

In France, the complicated Marseille method, used since “a time immemorial,”²⁶ gave tonnage as (effectively) the cubical number divided by 200. The 1681 ordinance of Colbert fixed the *tonneau* at 42 *pieds* cubed (913 liters, the same as the British tun), but the way it was measured was open to interpretation. Over time, French authorities received many proposals for new methods of admeasurement, often appended to treatises on commerce or agriculture²⁷; in one instance, they solicited advice from the Academy of Sciences (described later in this chapter). These systems were invariably rejected or went unused, and no system to replace the Marseille method was put into place until after the French Revolution.

By the 1700s, admeasurement had gone from being a simple accounting practice used for business to an administrative tool used by governments to bring some standardization into customs collection and charter rates. These rules soon became anything but “standard.” To take Britain as an example, there were separate rules used by the Navy Board, Parliament, and the various customhouses in the port cities; there were different measurements for the cubical number; measurements varied as to whether they were to the inside or outside of the structure; and the divisor could be 90, 94, 96, 97.5, or 100. There would be no reasonable conformity until the Moorsom system was instated by the British Merchant Shipping Act of 1854, and adopted internationally by 1885.²⁸

For constructors, the emphasis on cargo tonnage as the measure of the ship (even warships) meant that they had little reason to think in terms of displacement tons. This fact partly explains the long delay of many countries in adopting displacement tonnage as a unit of measure, as both constructors and owners (including admiralties) continued to apply the simpler admeasurement rules and avoided the more exact measures required for correctly calculating displacement. This was especially true in Britain, where navy ship plans continued to quote measurements in volumetric tonnage rather than displacement tonnage until the 1830s.

Calculating Displacement

As stated, tonnage measurements were developed to estimate profitability by establishing cargo capacity. Archimedes’ “principle of hydrostatics”—that the weight of a floating object is equal to the weight of the volume of liquid it displaces (described later in this chapter)—was well known, though not universally accepted, since its discovery circa 220 B.C. Yet this theory was not applied to ships for almost 2,000 years.

Displacement tonnage was not seen as a useful unit of measure for either the constructor or the owner, in the absence of any workable theory of stability or ability to estimate weights. So why, and when, did displacement tonnage come into use? It appears that there were two reasons for this: the development of the gun port and the measurement of cargo deadweight tonnage.

Early Measurements

Long before displacement calculations were begun, nations and city-states put tight controls on ships' freeboard, the distance between the load waterline (the draft at which the ship is fully laden) and a fixed point, such as the top of the hull or a gun port, in order to protect the high value of their cargoes. In Venice, the *Capitulare Navium* (Maritime Statutes) of 1255 established load waterlines according to the age of the ship, using an iron cross fixed to the hull.²⁹ One hundred years later, the Republic of Genoa adopted a statute that established freeboards for different routes based on sea conditions: higher for the open waters of the Bay of Biscay, lower for the protected Mediterranean.³⁰ There was a clear appreciation for the practical requirements of weight control, based on the expected weather and sea conditions and the state of the ship, even if there were no means of predicting those requirements during its construction. The actual load waterlines were not marked on the hull, and were rarely marked on drawings in ship manuscripts prior to about 1650.³¹

One difficulty in the widespread adoption of displacement calculations was that Archimedes' principle was often poorly understood in practice. As discussed in chapter 3, the science of mechanics was dominated by Aristotelian philosophy until the 1600s. Many scientists—especially in the Jesuit schools—adhered to Aristotle's notion that the properties of floating and sinking were due to the relative weight of the material or the shape of the body.³² This belief was so prevalent that in 1611, Galileo found himself defending Archimedes' principle against Aristotle's "shape theory" over the course of a three-day discussion on the matter.³³ Although the works of Galileo and Simon Stevin fundamentally shifted the scientific sentiment toward Archimedes, the implications were not fully assimilated for some time. In 1643, the Jesuit hydrographer Georges Fournier, in his widely read and influential book *Hydrographie* (Hydrography), gave a number of ill-founded reasons to explain why constructors did not estimate the displacement of ships, such as "There is a difference in the weight of parts that are in the water and those in the air" and "The same piece may be partly in water and partly in air, and the part in the water weighs less." He went on to state:

For all these reasons, and others, I conclude that it is morally impossible [*moralement impossible*] to be able to precisely determine and give general practice by which one can know the force

which will support a vessel. Also, I know of no mathematician who has attempted this, even none who has proposed the question.³⁴

Displacement Calculations for Warships

Impossible or not, the rapid evolution of the warship that began around 1500 would compel constructors to develop ways of calculating load waterlines, and thus displacement, during the design phase of the ship. The introduction of the gun port appears to have been the principal catalyst for this. Although the concept of putting hinged openings close to the waterline was much older, they tended to be loading ports that would stay closed at sea. The invention of gun ports was attributed to a constructor in Brest named Descharges in 1501,³⁵ and they came into common use by the 1540s. Gun ports would necessarily be open at sea, and were susceptible to down-flooding through heel or wave action if not located high enough above the water (as happened to the *Mary Rose*).³⁶ As described in chapter 1, the gun port multiplied several times over the firepower available at sea, by allowing the carriage of several rows of heavy guns, but this in turn required heavier framing, decking, and planking to support the weight. This immediately led to a precarious situation: at the same time ships were getting heavier, and thus deeper in the water, with great uncertainty as to how deep they would float, constructors were putting holes in the sides of the ship close to the waterline, which left little room for such error. The way out of this dilemma was to actually calculate the displacement, and thus the draft, to ensure that there was adequate freeboard to the gun ports.

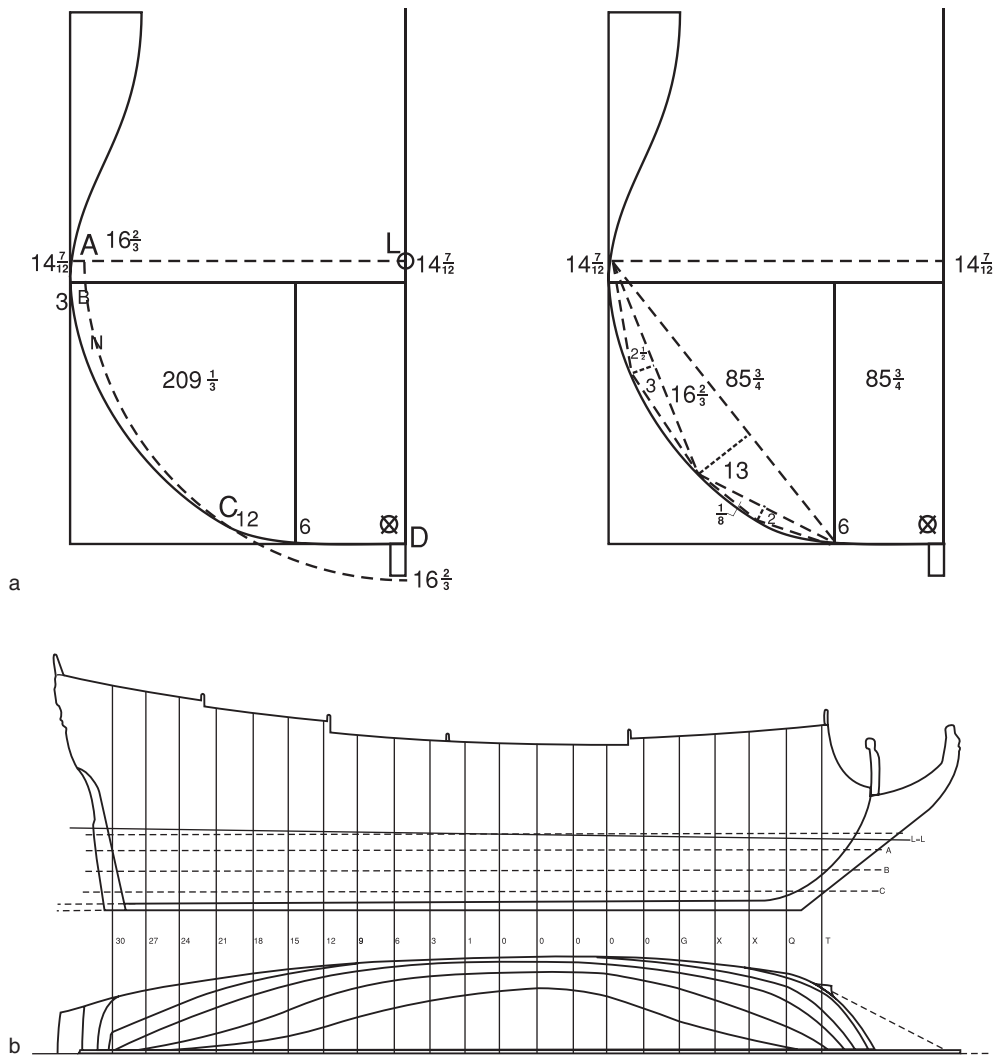
There is evidence that some British constructors were estimating load waterlines by the 1630s, although it was probably not common practice. The contract drawn up in 1634 by the constructor Phineas Pett for *Royal Sovereign*, the largest warship ever built at the time, called for a “draught of water” (full load) of 6.5 meters, a “swimming line” (light load?) of 5.7 meters, and tonnage “by the draught in water” of 1,661 tonnes.³⁷ In the same year, two of Phineas Pett’s relatives (his son and his nephew, both named Peter) were building ships in Woolwich and Deptford, and providing accurate estimates of their draft and freeboard to gun ports, well before launch.³⁸

This was certainly the case by 1665, when the Royal Navy commissioned several constructors to build 60-gun frigates; the contract with the Navy Board called for “their guns to lie 4-1/2 foot [1.2 meters] from the water.” Samuel Pepys, then an influential member of the Board (later secretary of the Admiralty), called this “another great step and improvement to our Navy, put in practice by Sir A.D.”³⁹ “Sir A.D.” was of course Sir Anthony Deane, and though Pepys’s admiration of his skills was overly effusive, Deane was widely regarded as the foremost constructor of his day. The French, in

particular the Colbert family, considered “Mr. Deane of Portsmouth as the best carpenter in all of England,”⁴⁰ and, as mentioned in chapter 2, Louis XIV commissioned two yachts from him. Deane had a distinguished record of naval construction; during his ten years as a shipbuilder before being appointed to the Navy Board, he built 25 ships and was responsible for developing the highly successful 70-gun ships, which formed the backbone of the Royal Navy until their replacement by 74-gun ships in 1755. Deane’s reputation and career were also helped considerably by the rise of Pepys to secretary of the Admiralty; although only five years older than Deane, Pepys had become his mentor and supporter. At Pepys’s request, Deane wrote a manuscript in 1670 on his ship design methods, titled “Doctrine of Naval Architecture.” Though it was never published, it was widely circulated within the Admiralty.⁴¹

Pepys several times credited Deane with discovering how to determine a ship’s draft,⁴² although Deane himself stated that “no-one can be a good shipwright who is not perfect in this matter.”⁴³ Although previous works by William Bourne and Edmund Bushnell (described later in this chapter) show that Archimedes’ principle was known and applied in some circles, Deane’s “Doctrine” remains the best example of how constructors were using mathematics in their day-to-day work during the 1600s. In it, he demonstrated two methods to calculate the sectional area underneath the assumed waterline at each “bend” or frame of the hull, using either an approximation for the area of a quarter-circle or by dividing the area into rectangles and triangles (see figure 4.2). Deane then divided the hull into 21 bends along the length of the ship (modern practice is to use 20 frame stations). The areas were then multiplied by the distance between the “bends” and divided by the density of the water to obtain the ship’s displacement.⁴⁴

It is important to note that Deane and other naval constructors were not attempting to estimate the weight and draft of the ship before it was launched, but rather to know how much ballast, stores, and other items to place on board after it was in the water. Deane calculated displacements at several waterlines, from the approximate draft at launch to required load waterline, to obtain displacements at various stages of construction, in a manner known as the “difference-in-drafts” method.⁴⁵ He categorically stated that once the ship is launched without “one stone of ballast, mast or rigging . . . you can easily know how much you must put in by measuring the ship’s body from that water she drew light to your assigned depth [i.e., draft at full load].”⁴⁶ Deane was using this technique even for unusual hull forms. In 1684 he prepared estimates of launch draft “at a medium draft . . . of 40 tunnes weight [i.e., deadweight]” for William Petty’s catamaran *Saint Michael the Archangel*, in part to settle several wagers over the craft’s performance.⁴⁷

**Figure 4.2**

Deane's methods for calculating displacement. Top: Calculation of sectional area at a "bend" (frame). Bottom: Lines plan showing location of each "bend." (After Deane, *Deane's Doctrine of Naval Architecture* [1670/1981], pp. 72, 124).

In Denmark, the problem of ever larger warships navigating the shallow Drogden Strait was a consideration that influenced constructors to begin calculating displacement. Only 7 meters deep at some points, the Drogden Strait lies between the island of Zealand and Sweden, and ships from Copenhagen had to pass through it to reach the North Sea. In 1692, at the very young age of 31, the mathematician Olaus Judichær became the chief constructor for the Danish navy, a position he would hold for 37 years. Before joining the navy in 1690, Judichær had been a student at the University of Copenhagen under the astronomer Ole Christensen Rømer, one of the founders of the French Academy of Sciences and later famous for correctly estimating the speed of light. Rømer was also a noted hydraulics engineer who had participated in the construction of the fountains at Versailles, and on his return to Denmark in 1681 he had helped in the design and construction of the Danish navy's drydocks at its base in Nyholm (just outside Copenhagen). Rømer taught Judichær, in addition to mathematics, the basic principles of hydrostatics and how to calculate volumes.⁴⁸

Judichær began indicating the drafts and displacements of his designs with the 54-gun *Prinz Carl* and *Prinz Wilhelm* in 1696. A clear indication of his precision is visible in his plans for the 90-gun *Elephanten*, built in 1703 and one of the largest ships in the Danish navy (figure 4.3). He carefully noted the drafts at three different displacements: launch, "best cruise," and a full load of 1,420 *lasts* (about 2,840 tonnes) that brought the great ship to within a meter of the Drogden Strait bottom.⁴⁹

Although it is not known for certain how Judichær performed his calculations, it was probably similar to Deane's method of inscribed triangles. Certainly, Judichær's successor, Knud Benstrup, was using that method for his displacement calculations of the 50-gun *Tre Løver* in 1728, as shown in figure 4.4.

Ironically, despite Benstrup's attention to this detail, he was later demoted and jailed for an alleged problem with the full load draft of the 90-gun *Christianus Sextus*. As built in 1733, the ship drew 6.6 meters aft, which was in fact just adequate to pass over the Drogden. However, this was about 15 centimeters greater than indicated on the plans, and an up-and-coming constructor named Diderich Lauritsen de Thurah used this fact to trump up a case against Benstrup. After a criminal investigation by the Board of Surveyors, Benstrup was stripped of his title as chief constructor and imprisoned for six years, clearing the way for Thurah to assume the post.⁵⁰

Cargo Deadweight

Deane and other naval constructors were obtaining "difference-in-drafts" while working from ship's plans, in order to estimate the ballast and other variable loads needed to bring the ship to its correct waterline. In the merchant world, this

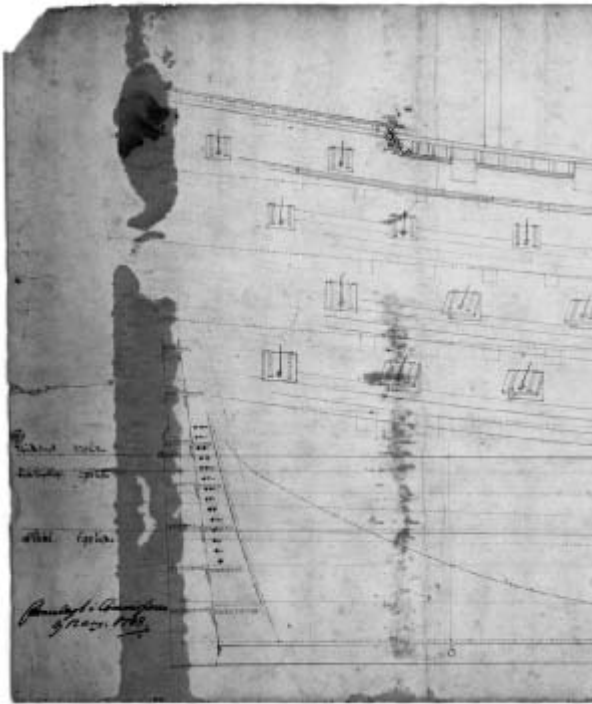


Figure 4.3

Plan of the Danish ship *Elephanten* by Olaus Judichær, with three different waterlines indicated (1702). Credit: Danish National Archives Rigsarkivet (Søetatens Tegningssamling A924).

difference-in-drafts method was sometimes employed to calculate cargo deadweight by measuring the hull volume from the outside. The process for doing this was first outlined in the British gunner and author William Bourne's 1578 book *A Treasure for Travellers*, as a means of estimating the strength and buoyancy (lifting capacity) of the "ships, ropes and lighters" needed to salvage a sunken ship. It involved bringing a ship aground and calculating its volume below the "swimming line" (i.e., waterline), using either poles and ropes or a "link engine" (a constructor's mold for taking off lines) to measure the overall cube, and subtracting the part of the cube outside the ship. The measurements were taken over the length of the ship and divided by the water density to obtain the displacement.⁵¹

Almost a century later, Denmark and the Netherlands were putting the finishing touches to a treaty that would establish a common method of measuring imported Norwegian timber for tax purposes. A common though cumbersome method of establishing deadweight for different ship classes was to load one ship of each type

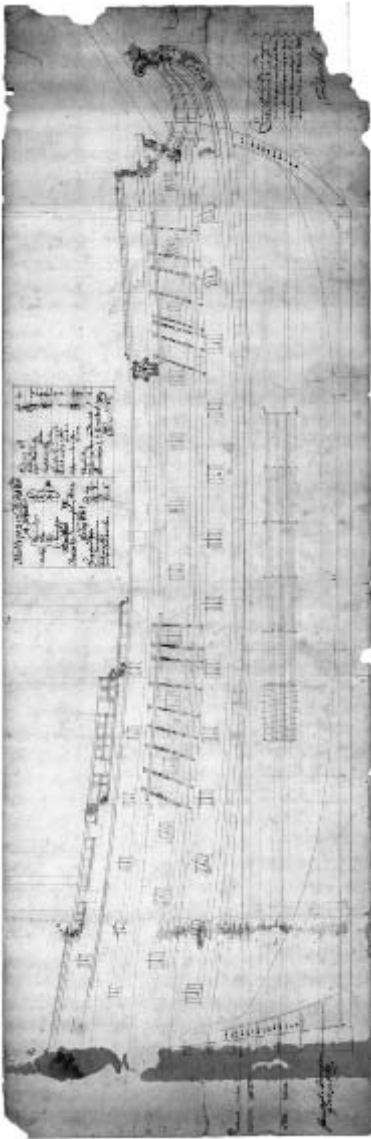


Figure 4.3 (continued)

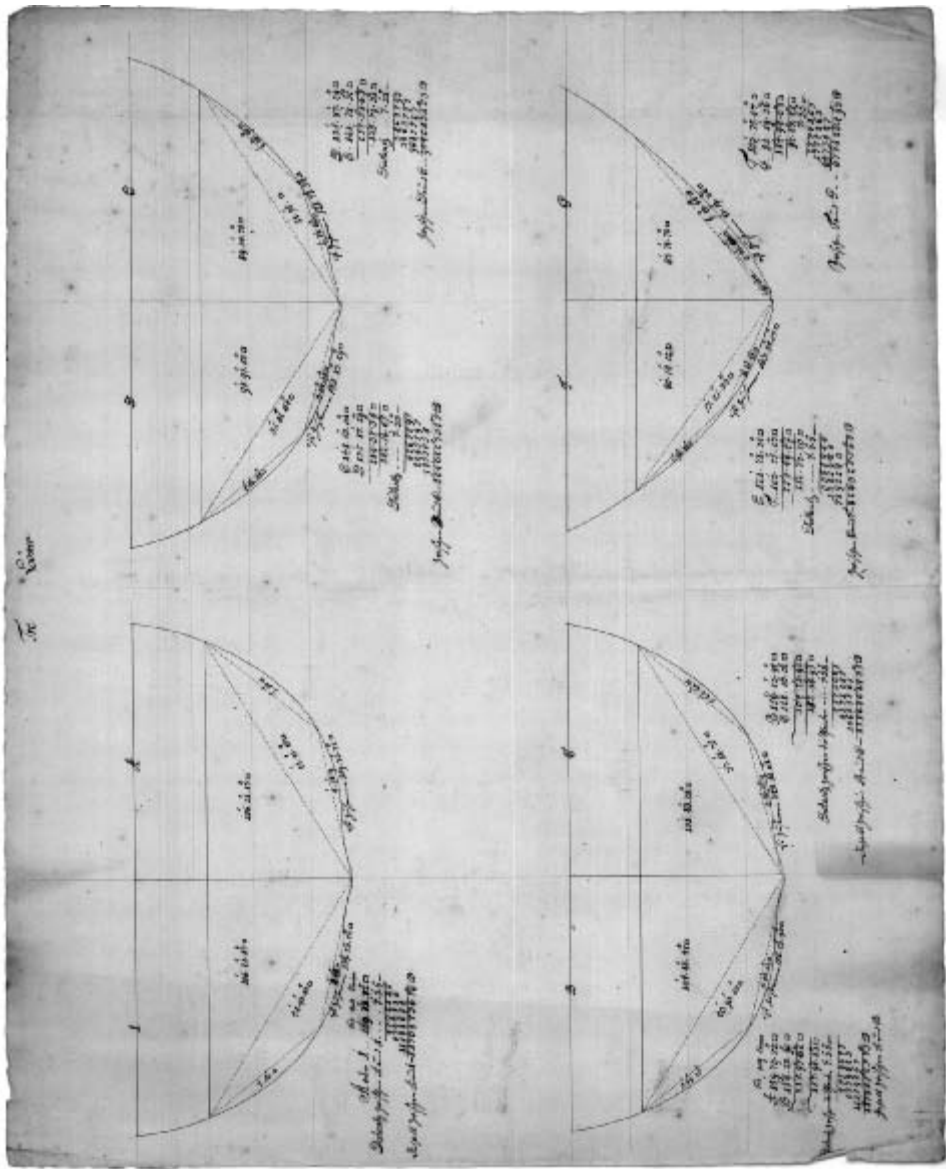


Figure 4.4
Knud Benstrup's displacement calculations for *The Løve* (1728). Credit: Danish National Archives Rigsarkivets (Søetstens Tegningssamling D249).

with known weights of cannon and cannonballs until the proper freeboard was reached.

In 1652 the Dutch mathematician Johann van Waveren Hudde identified the basic issue of measuring cargo deadweight by determining the difference between the weight of the ship empty and fully laden, using the difference-in-drafts method. He suggested to the Dutch authorities that they measure the water plane areas at each draft of an actual ship in the water (not from plans), by taking measurements to the hull from a line extended at the side of the ship parallel to the centerline. The space between the hull and an overall rectangle formed by the length and beam was then divided into trapezoids and triangles, the areas were calculated and summed, then multiplied by the difference in drafts and by seawater density, to obtain cargo tonnage. Although the suggestion was never used, Hudde's cousin Nicolaes Witsen reported it in his 1671 book on shipbuilding, *Aeloude en hedendaegsche scheeps-bouw en bestier* (Ancient and Modern Shipbuilding and Handling). Witsen noted that the admeasurers, working from pontoons moored to the ship, could obtain the correct results with about two hours' effort (see figure 4.5).⁵² In 1664 the British constructor Edmund Bushnell described a process very similar to Hudde's: subtracting the parts between the curve of the hull and a rectangle formed by the length and beam to obtain the water plane area.⁵³

In France, a more direct procedure was developed that would become the most widespread method for calculating displacement. In 1720, at the instigation of government officials wary of fraud in maritime commerce, the French Council of the Navy (the naval authority at the time) requested the Academy of Sciences to take up the question of admeasurement. The mathematician Pierre Varignon and the assistant director of the Academy, Jean-Jacques d'Ortous de Mairan, were placed in charge of proposing more accurate methods to the Council. Varignon developed his own mathematical method to calculate the volume of a ship's hull as a semi-ellipsoid.⁵⁴ Mairan, a physicist by training, consulted port authorities around France to ascertain the methods used in each port. A method previously submitted to him in 1717 by the intendant of Toulon, Jean-Hyacinthe Hocquart, used the difference-in-drafts method to determine deadweight. Hocquart proposed an older "method of trapezoids" he had learned, in which the water plane was measured directly from drawings and divided into equal-width trapezoids (see figure 4.6, top) in order to quickly and accurately obtain the areas.⁵⁵

On the advice of the retired mathematics professor Charles René Reyneau and the president of the Academy, Jean-Paul Bignon, Mairan asked the young (23) hydrographer Pierre Bouguer to verify the accuracy of Varignon's and Hocquart's methods by

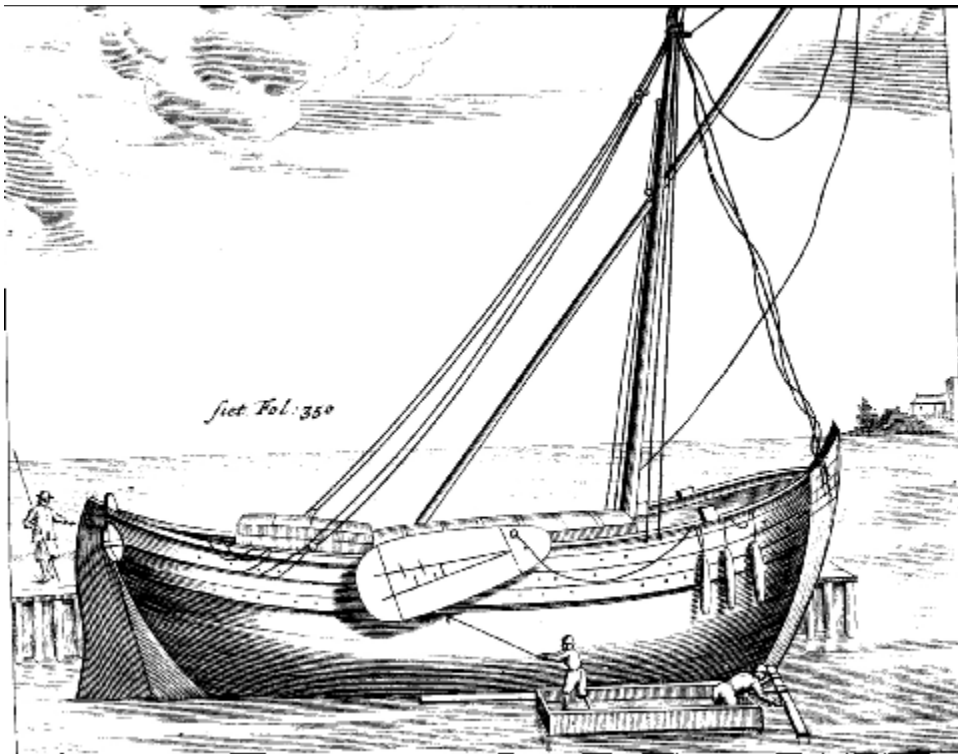
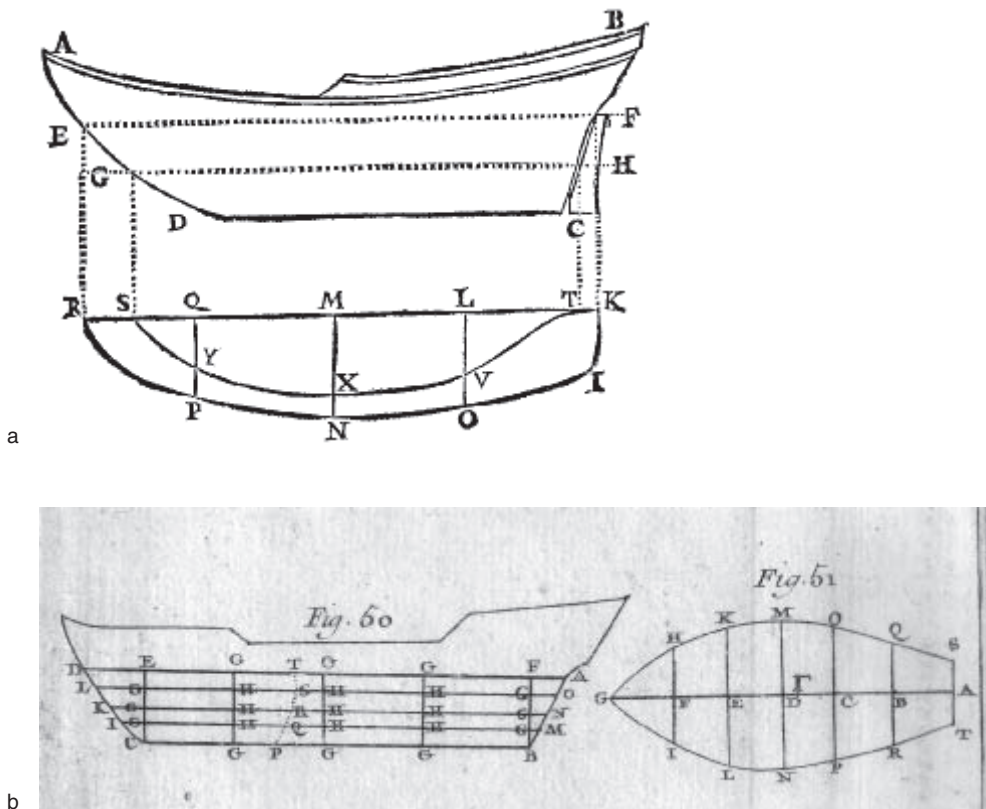


Figure 4.5

Method of Johann Hudde to calculate cargo deadweight (1652). (Yk, *De Nederlandsche scheepsbouw-konst open gestelt* [1697], p. 350).

actual measurement of two little harbor vessels in Le Croisic. Bouguer found that Hocquart's method was considerably more accurate. Although Mairan recommended Hocquart's method and the Academy endorsed it, the Council never adopted it and the old Marseille method continued to be used.⁵⁶ This marked Bouguer's entry into the circle of the Academy of Sciences, as well as the beginning of his involvement with naval architecture. Mairan would become his most important supporter at the Academy in subsequent years and, as described in chapter 3, proposed the subject of masting for the 1727 Academy prize. Bouguer refined the method of trapezoids for that prize: first, by dividing each water plane into many sections (Hocquart proposed only four sections); and second, by taking the areas of several waterlines to develop the entire volume of the hull—Hocquart took only one "slice"—a method he would recapitulate in *Traité du navire* (see figure 4.6, bottom).⁵⁷

**Figure 4.6**

Method of trapezoids to calculate areas. Top: Hocquart's method (1717). (Mairan, "Remarques sur le jaugeage des navires" [1721], p. 84). Credit: Bibliothèque Nationale de France/Gallica. Bottom: Bouguer's improvements (1727–1746). (Bouguer, *Traité du navire* [1746], plate 6).

Reconciling Weight and Displacement

Naval constructors were using the difference-in-drafts principle as a very practical means to estimate the amount of cannon, anchor, ballast, and stores and cargo needed to sink the ship, after it was launched, to its required draft. However, this did not provide the means to actually calculate displacement before the ship was in the water. That capability was simply not obtainable without a considerable investment by the dockyards to provide a detailed accounting of the materials during construction. The French constructor Blaise Ollivier would take the first significant steps in that direction.

In 1729, Blaise and his father, Joseph Ollivier, received the contract to build the 64-gun *Fleuron* at the Brest dockyard. Blaise had taken a voyage the previous year on the 74-gun *Achille*, carefully noting the ship's good and bad points in his notebook, and emphasized the need to develop an accurate estimate of the ship's weight and displacement in order to correctly judge its performance. He took up that challenge the following year with *Fleuron*. During the three-month design period, he divided the hull into numerous waterlines parallel to the keel and calculated displacements at each one, apparently using Bouguer's method of trapezoids that had just been published. Thus, he could take draft measurements at various stages after launch, and interpolate between waterlines to estimate the weight added at each stage of construction—for example, estimating the weight of masts and rigging as 57 tonnes.⁵⁸

These refinements foreshadowed an important step in the development of a workable theory of stability: the ability to estimate the overall weight of the ship *before launch*. This is done by calculating the weights of the various pieces of the ship directly, or by estimating via proportions to known weights of previous ships, and then summing the weights to create a final tally. Ollivier's work was one of the first attempts to provide this tabulation of materials in order to calculate weights and displacements; in 1743 he would refine his technique to tabulate all the weights for a 64-gun ship, calculating perhaps for the first time, the displacement of the ship before it was launched.⁵⁹

In fact, by the 1720s such tabulations were becoming increasingly important tools among French engineers and constructors, particularly within the dockyards. With the systematic use of ships' plans now well established, it became possible to develop accurate estimates for purchase of material and schedules for construction, as well as to provide a measure of control of expenses by state authorities. These meticulously calculated estimates (*devis*) were key to the efforts at standardization of ship types and the formalization of instruction on ship design.⁶⁰ The civil engineer and mathematician Bernard Forest de Bélidor, in 1729, called such estimates "the chief work of the engineer."⁶¹

Tabulations of material were also the key to calculating weights and, later, center of gravity. This fact was realized by the general commissioner of Rochefort, César Marie de La Croix; commenting on a proposed refit by Blaise Ollivier to the 72-gun *Lys*, he stated, "It seems necessary . . . to remit to the Council of the Marine, a table of weights of materials . . . of the body of the vessel, its masting, and artillery that each piece must support."⁶² Pierre Bouguer later echoed that idea for estimating weight and the center of gravity:

One can make use of the lists one already has in the ports; one examines in the same way the center of gravity of each piece; and one succeeds in that way, with little enough work, to resolve one of the problems of which the solution can contribute the most to perfecting construction.⁶³

Although the use of these lists amounted to an exercise in accounting, there still had to be a workable theory of stability for its proper application.

Early Development of Stability Theory, 220 B.C.–A.D. 1727

The physical principles of hydrostatic stability for floating bodies were first pronounced by Archimedes circa 220 B.C., although his examples were limited to simple geometrical shapes. Yet despite many important contributions and partially successful attempts by other scientists, a mature theory of stability for arbitrary three-dimensional bodies (such as ships) was not feasible until almost 2,000 years later, with the advent of infinitesimal calculus.

Archimedes and the Stability of Floating Bodies

Archimedes was born and lived in the Greek colony of Syracuse on the island of Sicily circa 287–212 B.C. As noted in chapter 2, he developed the lever law, in which he introduced the concept of “centroids” of quantities (areas, volumes, weights) into which the quantities can be “lumped” as concentrated effects so that moment equilibrium is retained. He also proposed a method for finding the “compound centroid” of a system of components (e.g., a center of gravity). Finally, he proved the critical “centroid shift theorem” (i.e., a rule for the shift of the system centroid when some quantity is added to, removed from, or shifted within the system. All of these concepts and results were essential physical principles that were prerequisites for his work on hydrostatics, which were enunciated in the treatise *On Floating Bodies*. This work, along with many others, was translated from a handwritten Greek copy into Latin by the Dominican monk Willem van Moerbeke in 1269. This translation became the basis for all knowledge of *On Floating Bodies* for many centuries, until in 1906 a tenth-century palimpsest of the work was rediscovered in a Greek monastery in Istanbul (it is now at the Walters Art Museum in Baltimore). With the transcription and translation of this new work, historians have been able to reliably evaluate Archimedes’ contributions to hydrostatics.⁶⁴

The treatise began with a description of the properties of a fluid at rest:

Let it be supposed that the fluid is of such character that, its parts lying evenly [at the same level] and being continuous [coherent], that part which is thrust the less is driven along by that which

is thrust the more and that each of its parts is thrust by the fluid which is above it in a perpendicular direction, unless the fluid is constrained by a vessel or anything else.

Although Archimedes did not use the word “pressure” and the Greeks did not know that concept in antiquity, he did infer that parts under more pressure would drive parts under less pressure, so that a fluid cannot be at rest unless the pressure is uniform at a given depth, while the weight of a vertical column of fluid rests on the parts below it. From these very simple premises, which do not permit evaluating the local pressure anywhere in the fluid, he was able to derive the principles of hydrostatic equilibrium and stability of floating bodies. This was achieved by considering the equilibrium of the resultant buoyancy and gravity forces and of their moments.

Archimedes’ “principle of hydrostatics” was stated in book 1, proposition 5: “Any solid lighter than a fluid will, if placed in the fluid, be so far immersed that the weight of the solid will be equal to the weight of the fluid displaced.” The proof of this law, usually written today as

$$\Delta = \rho V,$$

where Δ = weight, ρ = fluid density; and V = volume, is brief and conclusive. It rests on the argument that in equilibrium the solid is at rest in a fluid at rest; thus, if the body is removed from the fluid and the cavity left by its underwater volume is filled with fluid matter, then the fluid can remain at rest only if the replacing fluid volume weighs as much as the solid. Otherwise, the fluid would not remain in equilibrium and, hence, at rest.

In book 2, Archimedes dealt with the stability of hydrostatic equilibrium by treating the special case of a solid of simple shape, a segment of a paraboloid of revolution of homogeneous material whose specific gravity is less than that of the fluid on top of which it floats. In equilibrium it floats in an upright condition. The stability is tested by inclining the solid by a finite angle to the vertical, but so that the base of the segment is not immersed. The equilibrium is defined as stable if the solid in the inclined position has a restoring moment tending to restore it to the upright condition.

For the homogeneous solid this stability criterion is readily evaluated geometrically by examining the lever arm between the buoyancy and the gravity force resultants (figure 4.7). The buoyancy force acts through the centroid of the underwater volume (B), which Archimedes found for the inclined paraboloid from theorems proven earlier. The gravity force or weight acts through the center of gravity (R) of the homogeneous solid. The conventional righting arm, the projection of BR on the horizontal, is positive. Instead of using this stability measure, Archimedes took a shortcut for this

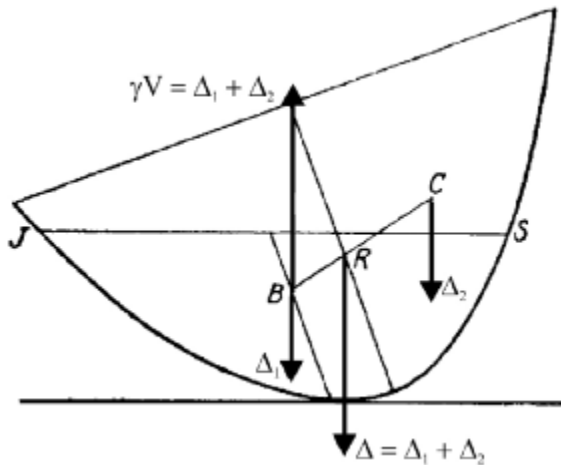


Figure 4.7

Archimedes' restoring moments and righting arms for inclined paraboloid (ca. 220 B.C.). (Nowacki, "Archimedes and Ship Stability" [2001/2002], p. 15).

homogeneous solid by splitting off and removing the weight of the submerged part of the solid Δ_1 and the corresponding equal share of the buoyancy force, which have no moment about B because they both act through B. Thus, only the weight of the abovewater section of the solid Δ_2 , acting through C, and the equal and opposite buoyancy force increment, acting through B, are taken into account. The centroid (C) is found from B and R by applying the centroid shift theorem when removing the underwater part from the system. This yields a positive "incremental righting arm" for the force couple of Δ_2 , acting through B and C, respectively. The restoring moment is thus positive, and the solid will return to the upright position.

This application of the hydrostatic stability criterion was limited to the special case of a homogeneous solid of simple parabolical shape. It demonstrated the physical principles of the hydrostatic stability problem for a finite angle of inclination. It did not extend to floating bodies of arbitrary shape and of nonhomogeneous weight distribution (i.e., actual ships). However, Archimedes laid the foundations that enabled others to treat the generalized case of the ship on the same fundamental grounds.

Simon Stevin and the Centers of Gravity and Buoyancy

After 2,000 years, the Dutch engineer Simon Stevin took the next step on the road to the metacenter. Stevin is credited with, among other things, the laws of hydrostatic

pressure, developed some 80 years before the French philosopher Blaise Pascal published similar observations.⁶⁵ His contribution to ship stability is found, however, in a two-page theorem buried between a treatise on pulleys and another concerning the mechanics of the horse bridle. He developed it in his role as military engineer, in order to show how high an assault ladder, mounted on a ship to scale a fortress wall, could be erected. The important observation, shown in figure 4.8, was that the center of buoyancy of the immersed hull (L) must be in the same vertical line as the center of gravity of the ship (point O). Stevin's proof was to imagine removing the hull from the water and replacing it with an equal volume of fluid; the center of the "hole" and the center of the water that replaces it must be in the same vertical line.⁶⁶

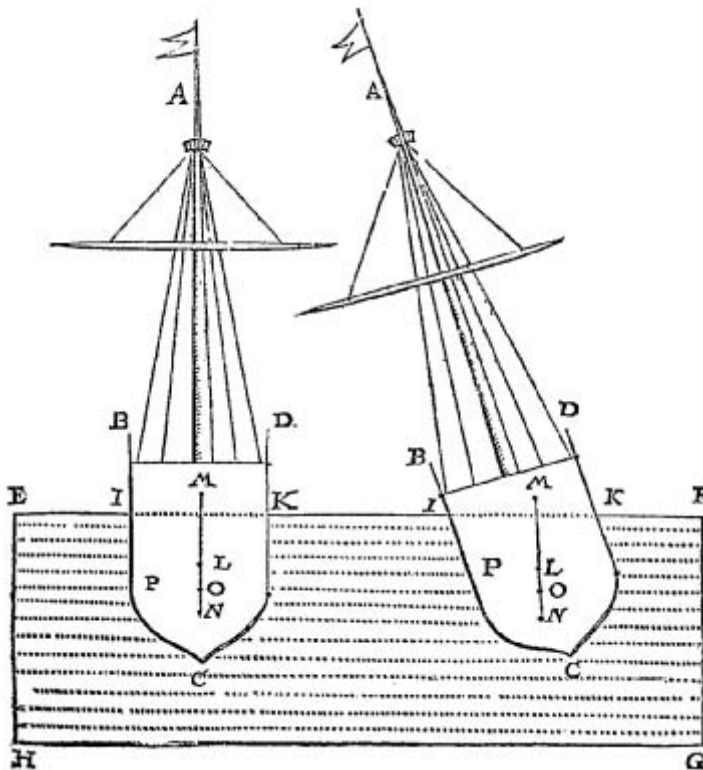


Figure 4.8

Stevin's proof for centers of gravity and buoyancy (1608). (Stevin, *Les Oeuvres mathématiques de Simon Stevin*, vol. 4, *L'Art pondéraire* [1634], p. 512). Credit: Bibliothèque Nationale de France/Gallica.

Stevin assumed without argument that the center of gravity must always lie *below* the center of buoyancy, or the ship would tip over. This was an understandable error, and not just because “common sense” would dictate that the supporting force must be above the center of gravity in order to be stable, in the way that a weight on a string must be below its attachment. At that time, sailing ships typically carried a large percentage of their displacement in the form of ballast and stores quite low in the hold, and without proper calculation of weights and moments—not done until over 100 years later—even the most mathematical constructor would naturally assume that the overall center of gravity of the ship was not far above the ballast line.⁶⁷

Extensions of Archimedes

In 1650, at age 21, the Dutch physicist Christian Huygens made an excursion into hydrostatic stability, which he never published and apparently never circulated. His treatise “De Iis Quae Liquido Supernatant” (Bodies Floating on Top of a Liquid) applied the method of Archimedes to the stability of floating homogeneous solids of simple shape, reconfirming Archimedes’ results and extending the applications to floating cones, parallelepipeds, and other shapes, at the same time studying the stability of these solids through a full circle of rotation (figure 4.9). He recognized that for homogeneous, prismatic solids, their specific weight and their aspect ratio are the essential parameters of hydrostatic stability. He did not cite Stevin’s observations on the centers of gravity and buoyancy; however, he did make use of Stevin’s principle of virtual work as a means of describing equilibrium. In his later years he looked back on his work with some antipathy, not considering it to be of sufficient originality to publish.⁶⁸

In 1700 the French mathematician Antoine Parent looked at the motions of a floating body, also extending Archimedes’ principles for a parabola to other conic shapes. He was the first to describe as a cycloid the path of the centers of gravity and buoyancy of a floating body in roll (figure 4.10). Parent assumed, without explanation, that the center of gravity could lie above the center of buoyancy, though he defined the state of equilibrium as where the two centers are closest (g and b). However, Parent’s construction was purely mathematical and not applied to ships.⁶⁹

Paul Hoste and Early Concepts of Stability, 1697

The French mathematician Paul Hoste took the first faltering steps toward providing a mathematical basis for understanding ship stability, and not just the stability of floating geometrical shapes, in his 1697 synthesis of naval architecture, *Théorie de la construction des vaisseaux* (Theory of the Construction of Vessels). Using the foundering

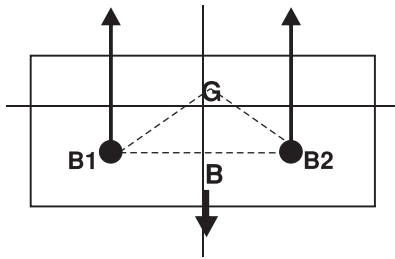


Figure 4.11

Hoste's explanation of how the center of gravity can be above the center of buoyancy (1697). (After Hoste, *Théorie de la construction des vaisseaux* [1697], fig. 47).

of *Lune* to introduce the chapter on stability, Hoste assumed, without citing Stevin, that the center of gravity (modern notation G) could be above the center of buoyancy (modern notation B), as shown in figure 4.11. However, his explanation of how the center of gravity could be above the supporting force without the ship tipping over, was that the buoyancy force to support G was equally divided between between the two halves of the ship (B1 and B2).⁷⁰ Hoste's error was compounded by his assertion that raising the center of gravity *improves* stability.⁷¹ Hoste went on to explain that the force the ship needs to carry sail is the force it needs to resist the sail force, which, as stated in chapter 3, he believed to be a function of the wind-on-sail force times the speed of the mast rotation. He stated: "If the center of gravity of the ship is known, the force with which it has to carry sail is easily known, which is no other thing than the product of the weight of the ship by the distance between these centers [of weight and displacement]".⁷² Or, in modern terms:

$$\text{righting force} = \Delta(KB - KG)$$

where: Δ = displacement (weight) of ship, KB = distance from keel to center of buoyancy, and KG = distance from keel to center of gravity.

Although he did not provide a theoretical means for determining this "power to carry sail," Hoste did furnish a procedure that could empirically demonstrate this—the inclining experiment. Hoste asserted that by measuring the angle of inclination due to suspending a weight M from a boom at a certain height, the "force to carry sail" can be determined.⁷³ In Hoste's geometry (using figure 4.12), with the center of gravity A and the center of buoyancy B as the fulcrum,

$$\text{inclining force} = \text{righting force}$$

$$M \times BF = \Delta \times BA.$$

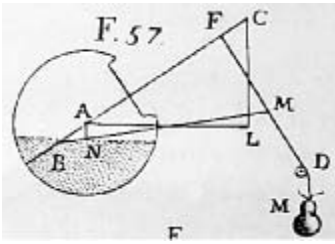


Figure 4.12

Hoste's diagram of an inclining experiment (1697). (Hoste, *Théorie de la construction des vaisseaux* [1697], chapter 2, plate 1) Credit: U.S. Navy Historical Center.

He therefore arrived at the following equation for the force to support sail:

$$\Delta BA = \frac{M}{\sin \angle BAN} (BA + AF).$$

In modern notation:

$$\Delta BG = \frac{W}{\sin \theta} BF.$$

Hoste, apart from being difficult to follow in his reasoning, made several fundamental errors (e.g., using the height of the suspended weight M as the lever arm, rather than the horizontal distance) later corrected by Bouguer. He used Aristotle's lever laws (lever arms $\times$ speeds are equal), still taught in Jesuit academies, instead of Archimedes' law (lever arms $\times$ forces are equal), so he could not incorporate Archimedes' shift of center of buoyancy for changes in body shape. Most important, his equations could not be used to actually help a constructor during design, since there were no means to determine the "overturning moment" of the sail, a problem that later plagued Euler's concepts of stability. However, Hoste had made the first attempt to express the stability of a ship in mathematical terms, and his book remained the only published inquiry into stability for almost half a century, with wide-ranging influence. For example, in the 1740s the Swedish constructor Gilbert Sheldon and the engineer Christopher Polhem made extensive use of Hoste's concepts, including his inclining experiment, when addressing the correct position for the center of gravity of ships to improve lading, handling, and speed.⁷⁴

Ship Stability in the Academy of Sciences Prize on Masting, 1727

As described in chapter 2, each of the three front-runners for the 1727 French Academy prize touched on the subject of stability in his memoir, but none explored it fully,

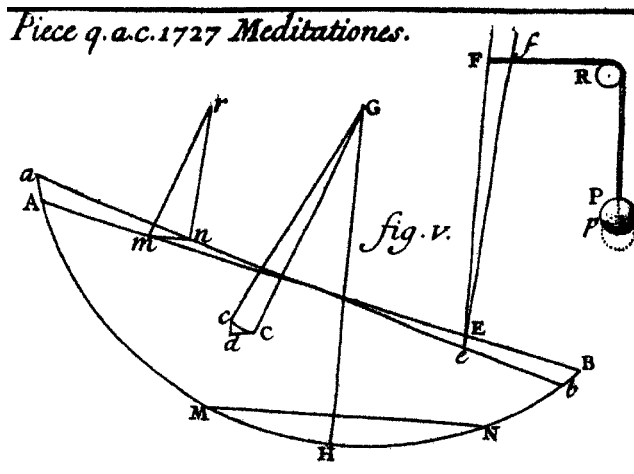


Figure 4.13

Euler's explanation of pitching moment due to wind force on sails (1727). (Euler, "Meditationes Super Problemate Nautico" [1727/1974], p. 17). Credit: Archives de l'Académie des Sciences, Paris.

principally through a lack of full understanding of Archimedes. These prize entries became the catalysts to the full exploration of stability that would occur just five years later.

Leonhard Euler, whose memoir “*Meditationes Super Problemate Nautico*” (Thoughts on a Nautical Problem) received honorable mention, recognized the need to balance the forward pitching moment of a ship with the appropriate restoring moment to maintain an acceptable angle of trim (figure 4.13). He also understood the same to be true for side heeling forces. However, without a fundamental knowledge of Archimedes’ hydrostatics, Euler was unable to define that restoring force.⁷⁵

By contrast, in “De la mâtûre des vaisseaux” (On the Masting of Vessels), Bouguer relied on theories developed by Hoste some thirty years before; however, where Hoste implied that the advantage of doubling is through an increase in the center of gravity, Bouguer invoked Archimedes (figure 4.14) to point out that the buoyancy of the added portion of the ship (A–D) moves the center of buoyancy Γ laterally, thus increasing the righting arm between the center of buoyancy and the center of gravity G (which he called the hypomoclon, of which more later).⁷⁶ However, this did not provide the insights into the evaluation of trim or heel angles, or of restoring moments, that were needed to properly address the effects of wind on sails.

Charles Étienne Louis Camus was perhaps the most progressive of the three in terms of hydrostatic stability. He recognized that he could not directly calculate the

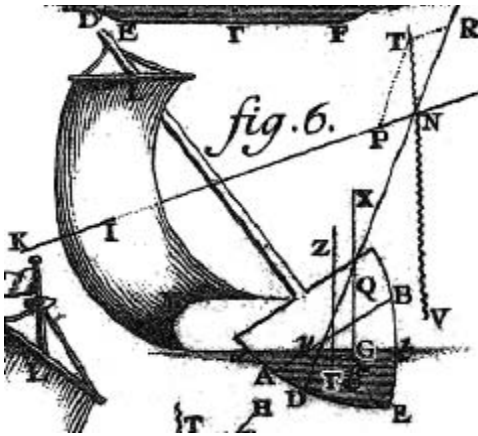


Figure 4.14

Bouguer's explanation of stability (1727). (Bouguer, "De la mâture des vaisseaux" [1727], plate 1) Credit: Texas A&M University Library.

stability of an individual ship, but that he could use stability criteria to provide proportional rules for masts and sails of different-sized ships. As shown in figure 4.15, the left-hand ship is used as the basis model. Camus asserted that the "righting energy" (in modern terms, "righting moment") is given by $\Delta \times R$, and the "heeling energy" of the wind (actually "heeling moment") is the product of the mast height times the sail area. In order for the right-hand ship to have adequate stability under sail, the proportions of its righting and heeling moments should be identical to those of the first ship.⁷⁷

Camus never followed up his memoir with further work on stability. By contrast, within a few years both Bouguer and Euler began tackling the subject, perhaps because after seeing all the prize entries published, they recognized the lack of a theory of hydrostatic stability as the gaping hole in their knowledge.⁷⁸ Their masting treatises also gave a glimpse into their method of investigation; Euler would continue to use the initial restoring moment as his criterion of stability, whereas Bouguer would use the idea of an intersection of forces at a point in space, similar to his *point vélique*, as the basis for his criterion of the metacenter.

After lying dormant for decades, a sudden burst of inquiry would result in three separate formulations of stability theory at almost exactly the same time. At least part of this rush of investigation can be attributed to the most ardent supporter of the application of science to naval power since Colbert: Jean-Frédéric Philippe Phélypeaux, count of Maurepas.

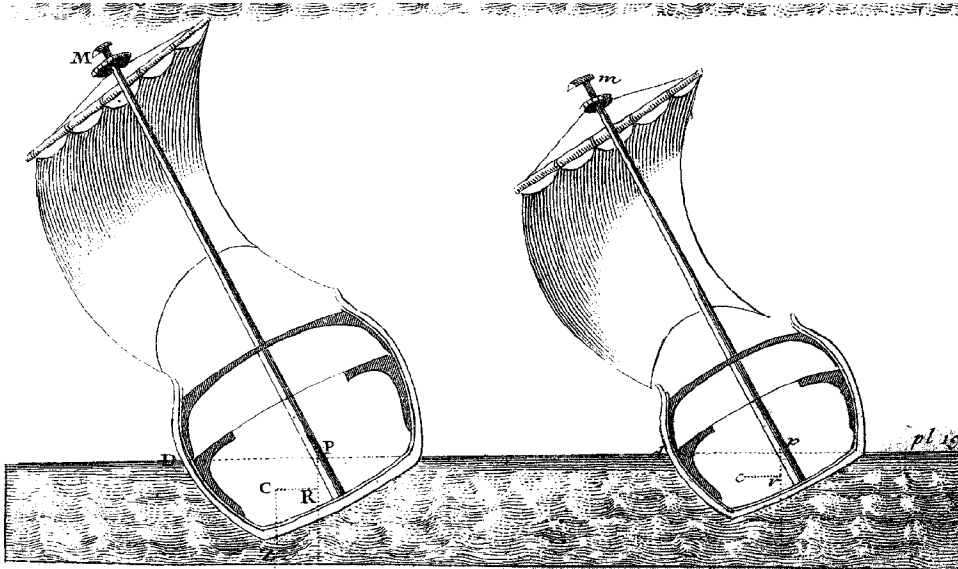


Figure 4.15

Camus's proportions of masts and sails based on stability criteria (1727). (Camus, "De la Mâtüre des vaisseaux" [1727], plate 3). Credit: Texas A&M University Library.

Convergence of Stability Theories, 1732–1736

Maurepas (figure 4.16) was born into a dynasty and groomed from infancy to become secretary of state (minister) of the navy, being the grandson and son of two previous navy ministers under Louis XIV (Louis Phélypeaux [1690–1699] and Jérôme Phélypeaux [1699–1715]). When Louis XV became king in 1723, Maurepas was appointed minister even though he was only 22 years old and rather frivolous in nature.⁷⁹ He was immediately faced with a fleet that had considerably diminished since the time of Colbert and Seignelay; under no illusion that the situation would change radically under the new king, he set about reordering the navy to make the best use of limited funds. Like Colbert, his principal aim in this was to improve France's external commerce; and also like Colbert, he did not trust his constructors to do this (with a few exceptions, such as Blaise Ollivier and François Coulomb)⁸⁰; rather, he saw the advancement and application of naval science as a means to this end. He became the honorary vice president of the Academy of Sciences and enthusiastically supported many of its activities, including the Geodesic Missions to Peru and Lapland.



Figure 4.16

Jean-Frédéric Philippe Phélypeaux, count of Maurepas. Etching by Gilles Edmé Petit from portrait by Louis-Michel van Loo (1736), château of Versailles. Credit: Réunion des Musées Nationaux/Art Resources, New York.

As discussed in the prologue, Maurepas took particular note of the young Pierre Bouguer (who was actually three years Maurepas's senior), and became his "protector" through much of his career. Soon after Bouguer won the 1727 Academy prize for his treatise on masting, Maurepas began providing him additional funds to carry on further research into ship resistance and strength, and Bouguer kept Maurepas abreast of his results. At the same time, Maurepas was also supporting the scientific work of César Marie de La Croix, then general commissioner of Rochefort, who had written on subjects including how to alleviate famine in the dockyards, and was investigating the use of magnetic compasses to determine longitude.⁸¹

It is unlikely that Bouguer and La Croix knew one another, or knew of one another's work. Yet from 1732 to 1736, simultaneously and independently, they began investigating the nature of ship stability. At exactly the same time, Leonhard Euler, by then a full professor at the Saint Petersburg Academy of Sciences, began *his* study of stability, in part inspired by La Croix's work. There had been no academic interest in ship stability since Hoste, and it is unlikely that either Maurepas or the Russian Academy was particularly interested in the subject. It appears from the few notes and letters on the matter that the simultaneous research into ship stability was due to a convergence of personal interests on the part of three rather different figures. The following evaluations are carried out as a systematic comparison of the three approaches.⁸²

César Marie de La Croix and the Hypomoclon

La Croix was the anomaly of the three. Bouguer and Euler were well-established scientists and mathematicians who had already published work on ship theory. La Croix, on the other hand, was the head of administration and finance for the Rochefort dockyard, by no means a technical position, and he maintained the records for the galley fleet. La Croix's interest in stability appears to have been inspired by the work he carried out for Maurepas on the refit of *Lys*, mentioned previously. He presented his manuscript on the subject of stability, "Parallèle des vaisseaux" (Parallel [Lines] of Vessels), in bits and pieces to Maurepas from 1732 to 1734. (The manuscript was in the Scott Collection of the Royal Institution of Naval Architects, but is no longer available to the public.⁸³) La Croix's focus was that of ship construction—finding the best proportions for the ship, as opposed to establishing a general theory of stability.

La Croix's theory was developed as follows:⁸⁴

Step 1: Premises and axioms La Croix asserted that weight and buoyancy ("pressure of water") are equal and opposite, act in the same vertical line, and are not altered by a submerged body. He did so without proof, without the use of equations, and

without mentioning Archimedes by name. He did not make any further hydrostatic assumptions.

Step 2: Magnitude of buoyancy force La Croix simply asserted Archimedes' principle that the weight of the floating body is equal to the weight of the volume of water it displaces. There was no further discussion of pressure forces.

Step 3: Measurement of volumes and volume centroids La Croix examined only the case of a two-dimensional box (parallelepiped), and did not give any results for determining either volumes or centroids of more complicated three-dimensional bodies. The assumption here is that the volume and centroid of the parallelepiped are known from basic geometry.

Step 4: Stability criterion As shown in figure 4.17, La Croix assumed the existence of a single "point of sustentation" F where buoyancy forces balanced, which he called the hypomoclon, an old architectural term meaning "fulcrum" that he apparently derived

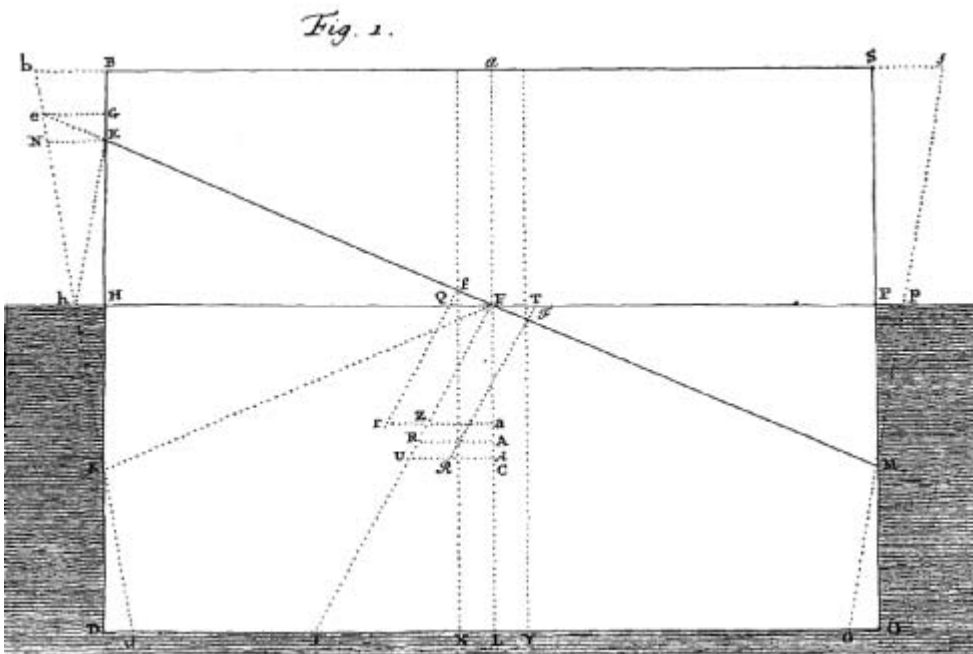


Figure 4.17

La Croix's assumptions on stability (1736). (La Croix, *Abstract on the Mechanism of the Motion of Floating Bodies* translation by John Knowles [1746/1775]) Credit: Texas A&M University Library.

from Bouguer's treatise on masting, but which Bouguer had defined as the centre of gravity. **F** is approximately equivalent to the modern-day center of flotation. La Croix compared a model suspended in air and held at the hypomoclon, with the angle of inclination of the body floating in water. The "correct" proportion for a floating body of breadth (*a*) at a specific draft (*c*) is where the angle of inclination (*x*) is less in water than in air.

Step 5: Evaluation of the criterion For a model suspended in air and held at the hypomoclon **F**, if

$$\sin x = \sqrt{(3c^2 - 2a^2)},$$

then the angle of inclination of the body would be the same as if it were floating in water. To ensure that the angle of inclination while floating is less than while suspended in air:

If $c > \sqrt{\frac{2a^2}{3}}$, then **F** would shift toward **f**, making the body more stable.

If $c < \sqrt{\frac{2a^2}{3}}$, then **F** would shift away from **f**, making it less stable.

In order to arrive at his equation, La Croix correctly employed the "shifting of wedges" technique that Bouguer used to account for the change in the center of buoyancy, but he incorrectly assumed that the hypomoclon in the waterline of flotation is always the "point of sustentation" through which the vertical force of buoyancy will act; in fact, the axis of motion will not remain fixed, but will translate horizontally as the body rolls.

Step 6: Results La Croix used this theory to explain why doubling a ship improves stability—it causes the center of flotation to shift farther toward **f**. Interestingly, La Croix described, but did not quantify, the maximum height of the center of gravity, above which the body will overturn; this corresponded to the metacenter in Bouguer's theory.

Step 7: Implications of the hypomoclon La Croix's purpose was to define the correct proportions of beam and draft for a ship. However, this extremely simplistic analysis did not account for other geometrical figures such as circles and ellipses, which more closely represented a ship's midsection. In addition, due to his lack of calculus, La Croix could not extend the results from the simple two-dimensional figure above to a generalized solid, which rendered the theory unworkable for real ships.

La Croix submitted his manuscript "Parallèle des vaisseaux" to the Academy of Sciences in early 1735; there it was examined and "not found to be true,"⁸⁵ as Leonhard

Euler would also find soon thereafter. La Croix, undeterred, immediately reprinted portions of the second volume of the manuscript in two parts in the *Journal de Trévoux* in 1735 and 1736, and as two small books—*Extrait du mécanisme des mouvemens des corps flottants* (Extract of the Mechanism of Movements of Floating Bodies) in 1735, and *Éclaircissemens sur l'extrait du mécanisme des mouvemens des corps flottants* (Explanations of the Mechanism of Movements of Floating Bodies) in 1736.⁸⁶ By this time, La Croix's favor with Maurepas had dwindled, and in 1737 he was sent to Martinique as commissioner, well away from the political and academic circles of Paris that he had once frequented.⁸⁷

Leonhard Euler and the Initial Restoring Moment

In 1735 La Croix sent a copy of his treatise to Johann Albrecht von Kroff, the president of the Saint Petersburg Academy, who asked Euler (by then a full professor) and Daniel Bernoulli (by then in Berlin) to review it. In an exchange of letters with La Croix in 1735–1736, Euler reviewed La Croix's assumptions, and politely but firmly pointed out the errors cited above. Euler demonstrated his grasp of the fundamentals of hydrostatic stability, stating that he had actually developed his solution some time before. Euler's first letter established his initial restoring moment criterion on hydrostatic stability. In his second review in 1736, in response to La Croix's rebuttal, Euler went beyond his first results, dealing with some other prismatic shapes (trapezoidal and triangular prisms), and alluded to his general approach to stability.⁸⁸ There is also some indirect evidence from his correspondence in 1736–1738 with the Danish naval constructor (and later instructor at the Danish Naval Academy) Frederik Wegersløff, then in London, that he had previously derived results for the stability problem.

The first publication of Euler's theory of hydrostatic stability was in his 1749 opus *Scientia Navalis* (Naval Science), which had actually been completed by 1741. It thus came to print a few years after Bouguer's *Traité du navire*, and Euler gave credit to Bouguer's work while carefully distancing himself from it, noting that he had no communication with Bouguer while he was in Peru. He also graciously acknowledged the motivation he received from reviewing La Croix's treatise, which prompted him to investigate more profoundly the transverse and longitudinal stability of ships.

Euler's derivation of his stability criterion in *Scientia Navalis* proceeded in the following steps:⁸⁹

Step 1: Premises and axioms In the first chapter of book 1, Euler rederived Archimedes' hydrostatic principle, using the then-novel infinitesimal calculus, by integration of the hydrostatic pressure distribution prevailing in a fluid over the surface of the body.

Lemma: The pressure which the water exerts on the individual points of a submerged body is normal to the body surface; and the force which any surface element sustains is equal to the weight of a straight cylinder of water whose base is equal to the same surface element and whose height is equal to the depth of the element under the water surface.

These brief axioms—the normality of pressure to a surface and the inferred equality of the pressure at a point in a given depth in all directions—were the first analytical formulations for the properties of a fluid, and are regarded as the necessary and sufficient conditions for the foundation of hydrostatics.⁹⁰

Step 2: Magnitude of buoyancy force From these premises Euler defined by integral calculus the buoyancy force as the pressure resultant, and the center of buoyancy, through which it acts, as the volume centroid of the submerged part. He reconfirmed that for equilibrium, the buoyancy and weight forces must act in the same vertical line and must be equal in magnitude and opposite in direction. He then illustrated these principles by examples of simple shapes such as parallelepipeds and prisms of triangular and trapezoidal cross section. For each of these solids he found the possible equilibrium conditions over a full circle of rotation as a function of the specific weight of these homogeneous solids, not unlike Huygens in his unpublished treatise of 1650.

Briefly digressing from hydrostatics, Euler then discussed the resulting motions of a floating body if it is temporarily displaced from its “upright” equilibrium position. Here he explained the “lumping” of masses in their center of gravity (CG), introducing the definition of the principal axes of inertia for ships and thereby underscoring the significance of the CG as a reference point (e.g., for decomposing a resulting motion into the translation of the CG and the rotation about it. Euler would also adhere to the CG as his system reference point when later returning to ship motions.

Step 3: Measurement of volumes and volume centroids Euler confined himself to analytical definitions of stability criteria, volumes, centroids, areas, moments of inertia, among others. He did not address their numerical evaluation at all. He took for granted that once the shape of the ship or body is defined by some function, the integrations can be readily performed. In his examples he usually dealt with simple shapes in which the integrations can be performed in closed form.

Step 4: Stability criterion In chapter 3, the main chapter on hydrostatic stability, Euler immediately defined his stability criterion thus: “The stability which a body floating in water in an equilibrium position maintains, shall be assessed by the *restoring moment* if the body is inclined from equilibrium by an infinitesimally small angle.”

He illustrated this principle by discussing cases of unstable, neutral, and stable equilibrium of ships, and added that it is necessary to quantify stability in terms of the

restoring moment because even a stable ship may be placed in danger by external heeling moments and may require righting moments of greater magnitude (i.e., the issue is not only whether the ship is initially stable or not, but also how much “stability capacity” it has).

Step 5: Evaluation of the criterion Euler then entered into the determination of the restoring moments by first examining a planar cross section of arbitrary shape (or thin disk) floating upright (figure 4.18). The figure AMFNB = AFB is inclined by a small angle dw so that the new floating condition has the waterline ab . Since the center of gravity G remains Euler’s reference point, also, for later purposes, he drew the parallel lines MN and mn to the waterlines before and after inclination, and also through G . The center of buoyancy of the cross section is designated by O . A normal VOo to the inclined waterline is drawn through O . The equality of the immersed and emerging wedges requires that ab intersect AB at the center point C so that $AC = BC$.

Let the displacement per unit length and the equal buoyancy force of the cross section before inclination be denoted by $M = \gamma(AFB)$. For the inclined position the restoring moment is composed of three contributions:

1. The effect of the original submerged volume forming a positive restoring couple of forces through G and V :

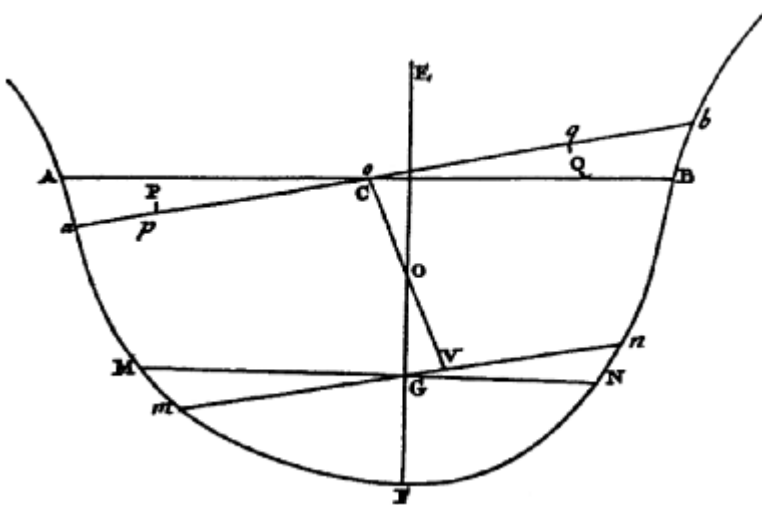


Figure 4.18

Euler's's figure for centroid shift in the inclined cross section, 2-dimensional case (1749). (Euler, *Scientia Navalis* [1749/1968/1972], vol. 1, fig. 39).

$$M \cdot GV = M \cdot GO \cdot dw.$$

2. The effect of the submerged wedge CBb, whose cross section area is

$$\frac{BC^2 dw}{2} = \frac{AB^2 dw}{8}$$

and whose restoring moment about G hence is

$$\gamma \frac{AB^2 dw}{2} (qo + GV),$$

$$\text{where } qo = \frac{2}{3} Cb = \frac{1}{3} AB.$$

3. Likewise, for the emerging wedge ACa the restoring moment is

$$-\gamma = \frac{AB^2 dw}{8} (po - GV),$$

$$\text{where } po = \frac{2}{3} Ca = \frac{1}{3} AB.$$

For all moments combined, replacing γ with $M/(AFB)$:

$$M_{\text{REST}} = M \cdot GO \cdot dw + \frac{M(AB^2 dw)(po + qo)}{8AFB} = Mdw \left[GO + \frac{AB^3}{12AFB} \right].$$

The expression in square brackets has the dimension of a length and corresponds to Bouguer's result of the metacentric radius.

Euler then arrived at the general three-dimensional case of a floating body of arbitrary and asymmetrical shape, with the cross-section shown in figure 4.18, whose water plane through A–B is drawn in figure 4.19. He denoted:

M = displacement or weight of body

V = submerged volume

GO = distance between CG and CB, positive for O above G

CD = reference axis of water plane through centroid of water plane area, parallel to axis through G

$CX = x$ = abscissa from origin C

$XY = y$ = ordinate in upper part of water plane

$XZ = z$ = ordinate in lower part of water plane

p and q = area centroids of upper and lower parts of water plane

P and Q = equivalent pendulum lengths of water plane area parts from axis CD

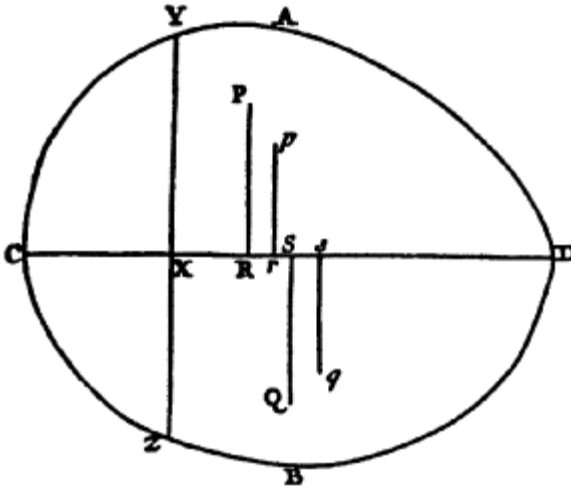


Figure 4.19

Euler's figure for the derivation of the stability criterion for a body of arbitrary shape, 3-dimensional case (1749). (Euler, *Scientia Navalis* [1749/1968/1972], vol. 1, fig. 48).

With

$$pr = \frac{\int y^2 dx}{2 \int y dx} \quad qs = \frac{\int z^2 dx}{2 \int z dx}$$

$$PR = \frac{2}{3} \frac{\int y^3 dx}{\int y^2 dx} \quad QS = \frac{3}{2} \frac{\int z^3 dx}{\int z^2 dx}.$$

Now, since the axis CD runs through the water plane centroid:

$$\int y^2 dx = \int z^2 dx.$$

Hence,

$$PR + QS = \frac{2}{3} \frac{\int (y^3 + z^3) dx}{\int y^2 dx},$$

from which, in analogy to the planar case, the *restoring moment*, divided by the angle $d\omega$, for the ship becomes

$$M \left(GO + \frac{\int (y^3 + z^3) dx}{3V} \right).$$

In the special case of port/starboard symmetry ($y = z$), the equation becomes:

$$I_T = \frac{2}{3} \int y^3 dx; \text{ and } \frac{I_T}{V} = OM.$$

In the modern notation ($GO = \overline{GB}$, $OM = \overline{BM}$), the restoring moment simplifies into $M(\overline{GB} + \overline{BM}) = M \overline{GM}$.

Step 6: Results Euler's stability criterion was the initial restoring moment, divided by ($M dw$). Euler never used the word "metacenter." He illustrated this result by many examples for simple shapes of solids, even by an analytical formulation for a shiplike body with parabolic section shapes. But he did not present any numerical calculations for an actual ship.

Step 7: Implications of the initial restoring moment Euler clearly distinguished between and addressed both transverse and longitudinal stability, and derived an expression for combined heel and trim under oblique sail force moments, deriving the oblique restoring effects by rotation of the reference axis from the principal axes. He noted that to assess stability, one must know the ship's displacement, the centroids CB and CG, and the water plane area and shape, from which the restoring moment can be inferred (without using the metacenter). He also pointed out that to improve stability, one must lower the CG, raise the CB, and/or widen the beam (e.g., using doubling).

Later, in his abbreviated treatise *Théorie complete de la construction et manœuvre des vaisseaux*, published well after Bouguer's metacenter theory had taken hold, Euler continued to illustrate the initial restoring moment as the principal stability criterion for ships.

Pierre Bouguer and the Metacenter

Bouguer probably began formulating his theory of stability around 1732, after he had moved to Le Havre, for he tested it using the little 18-gun frigate *Gazelle*, laid down in that dockyard in May 1732 and delivered in January 1734.⁹¹ However, no letters or manuscripts from that period survive to confirm this, and his derivation of the metacenter did not appear in print until 14 years later.⁹² The following steps illustrate Bouguer's derivation of the metacenter in book 2 of *Traité du navire*.⁹³

Step 1: Premises and axioms Bouguer implicitly defined the hydrostatic properties of fluids, based on the principle of hydrostatics that weight and buoyancy are equal and opposite, and act in the same vertical line. He did so without proof, without the use of equations, and without mentioning Archimedes by name, although he showed general familiarity with his work. He also implied through geometrical arguments that the pressure of the fluid follows a hydrostatic distribution with depth, and is everywhere normal to the surface of the submerged body.

Step 2: Magnitude of buoyancy force Bouguer resolved the submerged surface into very small elements (though without using any calculus notations at this point) and conceptually equated the vertical components of the hydrostatic pressure forces to the weight of the water column resting on top of the element in the interior of the submerged volume. Hence, the total pressure resultant is equal to the total weight of water filling the submerged volume.

Step 3: Measurement of volume and centroids Bouguer reprised the two methods for calculating the volume of the ship as a regular solid from the admeasurement study he performed for the Academy of Sciences in 1722: the first, to model the ship as an ellipsoid, as originally proposed by Varignon (which he did not endorse), and the second, to divide it into prisms, using the method of trapezoids he developed from Hocquart (refer to figure 4.6). Bouguer then digressed for many pages into using the method of trapezoids to calculate incremental waterlines for estimating a ship's payload capacity and tonnage. For finding the centroid of the underwater volume (the center of buoyancy CB), Bouguer explained in simple terms how to use the sum-of-moments method to determine the centroid of an object. He then derived the area centroid of a planar figure (two-dimensional case), then the volume centroid of a solid (three-dimensional case), which for a ship he called the "center of gravity of the hull." He gave several worked examples of how to evaluate these expressions numerically by the method of trapezoids.

Step 4: Stability criterion The center of buoyancy having been determined, Bouguer next explained why he chose the metacenter as the initial stability criterion, using the geometrical argument shown in the simplified figure 4.20.

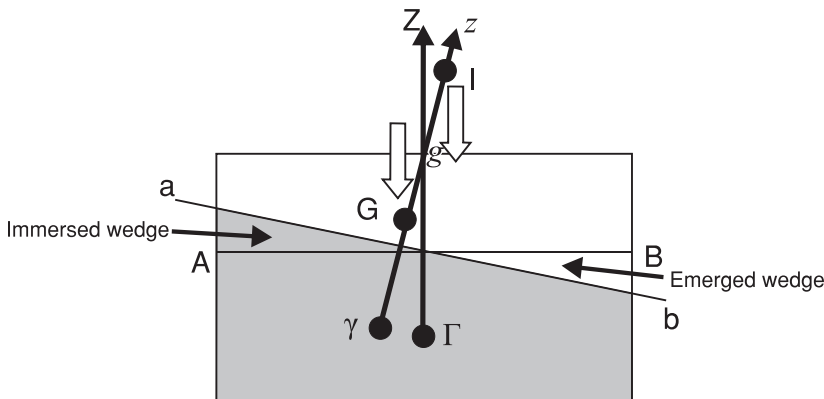


Figure 4.20

Simplified explanation of the metacenter.

The ship's center of gravity g is always in the same vertical line as the center of buoyancy Γ , but this geometry is not constant due to the ship's movement. If the ship has a very high center of gravity I , and moves even a little from the upright position (waterline A–B) to another position (waterline a–b), it is no longer statically stable; the center of buoyancy moves from Γ to γ (i.e., away from the vertical of the center of gravity), and the vertical force of buoyancy shifts from Γ – Z to γ – z . The ship's weight, centered at I and on the opposite side of the inclination from the new center of buoyancy, tends to push the ship even farther over, rendering it unstable. However, if the center of gravity of the ship is at G , below the intersection g of the upright and inclined vertical forces of buoyancy, then the center of gravity is on the *same* side as the new center of buoyancy, and the resulting force always tends to restore the ship to the horizontal.

Bouguer stated in his definition of the metacenter:

Thus one sees how important it is to know the point of intersection g , which at the same time it serves to give a limit to the height which one can give the center of gravity G , [also] determines the case where the ship maintains its horizontal situation from that where it overturns even in the harbor without being able to sustain itself a single instant. The point g , which one can justly title the *metacenter* [Bouguer's italics] is the term that the height of the center of gravity cannot pass, nor even attain; for if the center of gravity G is at g , the ship will not assume a horizontal position rather than the inclined one; the two positions are then equally indifferent to it: and it will consequently be incapable of righting itself, whenever some outside cause makes it heel over.⁹⁴

Like his *point vélique*, the metacenter was an imaginary point in space that defined the intersection of two forces. Bouguer never used the terms “stable” and “unstable,” but stated that G is either lower or higher than the metacenter g .

Step 5: Evaluation of the criterion Bouguer stated that the determination of this point of intersection g reduces to the question of the distance between the centers of buoyancy Γ and γ of the submerged body upright and just slightly inclined.

Using figure 4.21, Bouguer employed the all-important shifting of equal immersed and emerged wedges to determine this distance, by drawing a triangle between points 1, 2, and 3. Since the centers of buoyancy Γ and γ lie on the legs of that triangle, the distance Γ – γ must be proportional to the distance between points 1 and 2, and the distance between Γ and point 3 must be proportional to the ratio of the volume of the underwater hull and the wedges. This geometrical explanation set the stage for the second half of the explanation, the mathematical analysis of the mechanics of stability.

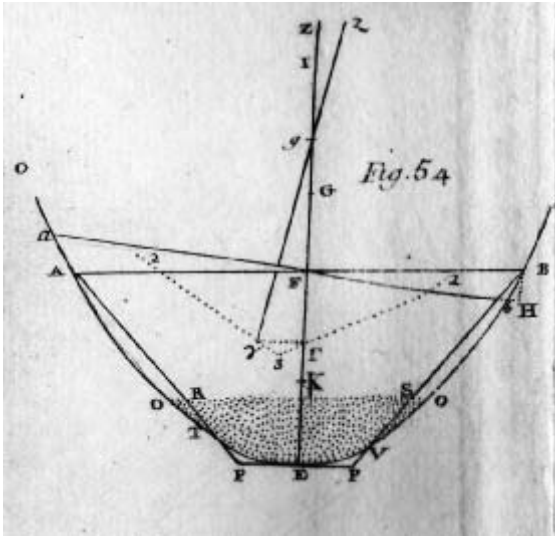


Figure 4.21

Bouguer's diagram of the metacenter (1746). (Bouguer, *Traité du navire* [1746], plate 6) Where: p = submerged volume, Γ = upright CB, γ = inclined CB, AB = upright waterline, ab = inclined waterline, I = CG of an unstable ship, G = CG of a stable ship, g = metacenter, 1 = centroid of immersed wedge, 2 = centroid of emerged wedge, 3 = centroid of body without wedges.

Step 6: Results In the next section, Bouguer used calculus to determine the three unknowns: the distance from point 1 to point 2; the volume of the wedges; and the volume of the hull. He imagined that figure 4.21 represents the largest section of the ship, which actually extends through the plane of the page in the longitudinal direction x , with the immersed and emerged wedges actually an infinite sequence of triangles of width y (the largest being $b = F - B$, or the half-breadth of the hull at the waterline) and height e ($H - B$) going through the length of the hull at a distance dx from each other; integrating, the volume of the wedge is

$$V_{\text{wedge}} = \frac{e}{2b} \int y^2 dx.$$

The second unknown is the distance between the centers of the wedges, point 1 to 2; but since the center of a triangle is two-thirds the height from apex to base, it is straightforward to obtain this distance as

$$\text{Distance } 1-2 = \frac{4 \int y^3 dx}{3 \int y^2 dx}.$$

The third unknown, the volume of the hull p , is derived using the method of trapezoids. Putting the three together, the distance is

$$\Gamma\gamma = \frac{2e \int y^3 dx}{3bp}.$$

Finally, observing that the triangle $\Gamma g\gamma$ (i.e., between the centers of buoyancy and the intersection of their vertical lines of force) is similar to the triangles formed by the immersed and emerged wedges, the height of the metacenter g above the center of buoyancy Γ is found, via Euclid, to be the now well-known equation for the height of the metacenter, also known as the metacentric radius, since it is applicable across the full rotation of the body:

$$\Gamma g = \frac{2 \int y^3 dx}{3p}.$$

In the modern notation ($G\Gamma = \overline{GB}$, $\Gamma g = \overline{BM}$), the height of the metacenter above the center of gravity is

$$\overline{BM} - \overline{GB} = \overline{GM}.$$

Step 7: Implications of the metacenter Bouguer developed in thorough detail both the theoretical and the practical aspects of the metacenter. He derived the metacenter for various solids (ellipsoid, parallelepiped, prismatic body) and presented the procedures for its practical, numerical calculation for ships. These explanations were detailed enough for practical applications and became the foundation for later textbooks.

But Bouguer also charged ahead beyond the initial metacenter for infinitesimal angles of heel when he introduced the concept of the *métacentrique* (i.e., the metacentric curve for finite angles of heel). First, he clearly recognized that the same physical principles and stability criteria apply to an inclined position of the ship as to the upright case. Second, he recognized that the metacentric curve for finite angles is in fact the locus of the centers of curvature of the curve of the centers of buoyancy, which form a class of curves known as evolutes. For a wall-sided ship (or parallelepiped) the metacentric curve is a cusp-shaped curve composed of two hyperbolas lying above the metacenter. His demonstration examples for the *métacentrique* show that he understood how to approach stability for finite angles of heel, though he never used a “righting arm” criterion.

On practical aspects of initial stability, Bouguer recommended against tumblehome (the sides of the ship inclining inward), suggesting that the widest point of the ship be no lower than where the maximum heel would be before it begins to tumblehome, or even that ship sides be straight or flared throughout.

Bouguer continued for almost 50 pages to outline the practical implications of the metacenter on hull design and outfitting. In many cases the implications were restatements of what constructors already knew; but he provided for the first time a rigorous analysis of why they were true. Bouguer emphasized that the greatest advantage to stability lies in increasing the beam. He claimed that the “stability” varies as the cube of the beam, although this is true only for the transverse moment of inertia I_T (in a real ship, an increase in beam would have other effects on overall stability). This also explained why girdling a ship improves stability, although Bouguer never explicitly stated this. He also analyzed the well-known fact that stability is improved by diminishing the weight of the topsides, and detailed how to accurately assess the effects.

Bouguer also correctly described for the first time how to evaluate the inclining experiment, for whose basic idea he credited Hoste (refer to figure 4.12), in order to determine Gg , the distance between the center of gravity and the metacenter (in modern terms, $\overline{GM}$). In figure 4.22, he demonstrated how to use a known weight suspended from a yardarm to incline the ship and measure the angle of heel. Using the law of similar triangles, he showed that the ratio of the ship’s displacement and the suspended weight is proportional to the ratio of Gg to the angle of heel and the distance the weight moves; on the assumption of small angles of heel, this allows Gg (i.e., the reserve of stability) to be calculated directly without knowing the exact position of the metacenter.

Bouguer also demonstrated how to use his metacenter by detailing the calculations of weights and centers of gravity for *Gazelle* while it was still being framed out. It is therefore curious that he did not verify this by performing an inclining experiment on the little ship.⁹⁵ Why not verify his metacenter theory using the same ship on which he had performed his calculations? As explained in the preface, Bouguer’s attention, like that of the rest of the Academy, had in 1734 suddenly turned to the question of the Earth’s shape, and he would not return to the metacenter until he was high in the mountains of Peru.

The Metacenter as a Multiple

In the 2000 years since Archimedes, almost no progress had been made on the theory of ship stability. Suddenly, at the same moment in history and within a span of three years, three men, working independently and separated by hundreds of miles, invented theories of stability that were remarkably similar. This phenomenon, termed

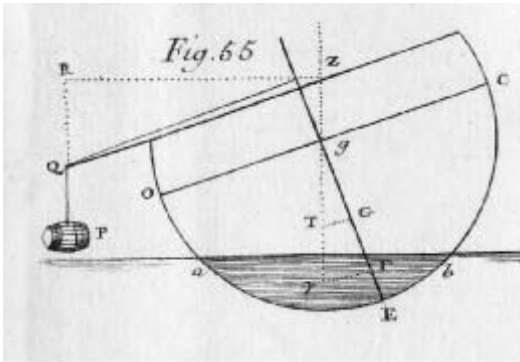


Figure 4.22

Bouguer's diagram of the inclining experiment (1746). (Bouguer, *Traité du navire* [1746], plate 6).

a “multiple” by the American sociologist Robert Merton, has perplexed historians for centuries.⁹⁶

Analysis

Modern analyses of multiples have focused on four aspects: priority, the study of the struggle to establish who first made the invention; genius, examining the individual traits that marked the invention; cultural maturity, establishing why and when the scientific knowledge and circumstances were ripe for the inventions to be made; and correspondence, whether the inventions were in fact the same. The case of the metacenter provides a few clues about each of these aspects.

Priority Multiples often result in a contest over who was first; for example, Newton's dispute with Leibniz over the development of the calculus. Studies seek to examine the cultural, organizational, and individual behaviors surrounding the battle for priority. In the case of the metacenter, this was never an issue; Euler always acknowledged that Bouguer published his results first.⁹⁷ Priority disputes appear to require *two* large egos; while Bouguer certainly had that trait (shown in his own priority dispute with La Condamine over the results of the Geodesic Mission, described in the epilogue), Euler was well known for his humility, generosity, and self-deprecation, so the requisite friction never developed.

Genius Although Bouguer and Euler were intellectual giants, La Croix appears to have been nothing more than a well-educated man with a broad interest in science;

and yet he developed many of the same insights into stability as Bouguer and Euler. In the case of the metacenter, the critical insight that allowed Bouguer and Euler to succeed where La Croix did not, was knowledge of the calculus.

Cultural Maturity The case of the metacenter provides a specific example of what “cultural maturity” means in terms of the knowledge required to be in place before the theory could mature, and the process by which that knowledge was accumulated. The elements needed for a complete theory can be organized into seven categories⁹⁸:

1. Conceptual experiments
2. Gravity and buoyancy forces
3. Concept of stable and unstable equilibrium
4. “Couple” of gravity and buoyancy forces as criteria for equilibrium
5. Shifting of wedges to calculate this couple and define the metacenter
6. Determination of the metacenter experimentally
7. Curve described by the metacenter for different angles of heel.

These categories are generally sequential; that is, the concepts developed in one are necessary for an understanding of the next. The discoveries leading to the metacenter did not, however, necessarily proceed in that sequential order. Table 4.1 shows these criteria.

The table makes it clear just how far Archimedes developed the theory, and how no real progress was made for almost two millennia afterward. In the 1600s, Christiaan Huygens and Antoine Parent extended the theory to other plane figures, Stevin and Hoste added several critical details regarding the positions of the centers of gravity and buoyancy, and Hoste was the first to attempt a systematic analysis of stability, including the concept of an inclining experiment. The table shows why no complete theory could exist before 1700. Knowledge of the calculus was not widespread on the Continent until the 1720s, so the convergence of Bouguer’s and Euler’s theories happened within a decade of a correct solution being hypothetically possible.

Studies of multiples often point to a general problem being worked on by many scientists, a situation in which it becomes almost inevitable that two or more arrive at the same conclusion simultaneously; the phrase often used is that it was “in the air.” In the case of the metacenter, stability theory was definitely *not* “in the air”; scientists were engaged elsewhere in problems of navigation and maneuvering, and in fact the earlier works on masting of both Bouguer and Euler showed none of the interest or insights on stability that they would exhibit just five years later. Nor was outside influence responsible; as stated, there was no clamor from the navies to fix the

Table 4.1
Criteria for developing stability theory

No.	Concepts and Methods First Described	Archimedes c. 220 B.C.	Stevin 1608	Huygens 1650	Hoste 1697	Parent 1700	La Croix 1732–36	Bouguer 1732–46	Euler 1735–49
1.	Conceptual experiments	✓							
2.1	Gravity force	✓							
2.2	Resulting gravity force of a system of weights	✓							
2.3	Buoyancy force, its magnitude and direction	✓							
2.4	Hydrostatic equilibrium, Archimedes' law	✓	✓	✓					
3.1	Concept of stable/unstable equilibrium	✓		✓					
3.2	Test of "small" displacement	✓							
4.1	Couple of gravity & buoyancy forces as equilibrium criterion	✓		✓					
4.2	Calculation of sign of couple for simple shapes	✓		✓					
4.3	Center of gravity in same vertical as center of buoyancy		✓	✓	✓	✓	✓	✓	✓
4.4	Center of gravity may be higher than center of buoyancy				✓	✓	✓	✓	✓
4.5	Explicit calculation of ship weight and center of gravity by summing of weights and moments						✓		
5.1	Method of wedges for stability calculations						✓	✓	✓
5.2	Infinitely small wedges							✓	✓
5.3	Use of calculus in deriving stability equation							✓	✓

Table 4.1
Continued

No.	Concepts and Methods First Described	Archimedes c. 220 B.C.	Stevin 1608	Huygens 1650	Hoste 1697	Parent 1700	La Croix 1732–36	Bouguer 1732–46	Euler 1735–49
5.4	Calculation of buoyancy force & direction for arbitrary shape							✓	✓
5.4	Use of the metacenter as a stability criterion							✓	—
5.5	Naming this point metacenter							✓	—
5.6	Stability criteria phrased in metacentric terms							✓	—
5.7	Stability criteria based on restoring moment							—	✓
6.1	Determination of stability by inclining experiment				✓			✓	—
7.1	Metacentric curve for finite angles of heel							✓	—
7.2	Founding of metacentric curve in the evolute							✓	—
7.3	Stability or metacenter calculations for finite angles of heel							✓	—

“stability problem,” and while Maurepas was certainly the supporter of Bouguer and La Croix, there is no evidence that he suggested to either the lines of research they should take.

Correspondence Analysis of multiples often reveals them to be similar solutions to quite different problems; the fluxions of Newton and the differentials of Leibniz were not shown to be the same until Euler did so almost 50 years after their first appearance. In the case of the metacenter, each man was looking at a quite different problem. La Croix was searching for the optimal ratio of beam and draft to build ships; Bouguer was interested in a practical means of assessing the stability of any ship, given its hull form and weights; and Euler developed a general mathematical model for stability of different shapes, without specific reference to ships.⁹⁹

Why Was the Metacenter Successful?

These three theories appeared at roughly the same time, yet only the metacenter became routinely used by constructors by the late 1700s. Because La Croix’s theory of hypomoclon was seen to be wrong by influential scientists at the French Academy of Sciences, it was never published in a journal or book under royal privilege, and had little distribution among constructors or navy administrators (La Croix was by then in Martinique and couldn’t “talk up” his ideas).

Euler’s theory suffered from three problems. First, his text was initially written in Latin, and by the mid-1700s, Latin was no longer the common language of science and engineering. Although he corrected this in 1773 by writing an abridged version in French, by then the idea of the metacenter had already taken hold. Second, Euler’s text was highly mathematical and contained no numerical solutions to guide the constructors in integrating areas, volumes, and centroids. Third, his criterion of the initial restoring moment was a physical quantity that required constructors to balance the wind or other heeling moment against the righting moment. Constructors were at that time working only with distances and areas, and the concept of force, much less the measurements needed to arrive at a “force balance” or “moment balance,” was unknown to them in practical terms.

Bouguer’s theory had several things going for it. An experienced professor of hydrography, Bouguer wrote in very accessible seaman’s French. He provided ways of numerically calculating physical quantities and gave worked examples; unlike Euler, who provided a global mathematical solution to all floating bodies, Bouguer specifically addressed ships, and used only as much mathematics as was necessary to arrive at a practical result. The metacenter itself was a geometric concept that was relatively easy

to imagine, and the solution was in units of length, a concept that constructors could immediately grasp. Most important, Bouguer's metacenter came on the scene at exactly the time Duhamel du Monceau was establishing his "Little Navy School," later the School of Engineer-Constructors of the Navy, that would train all future French constructors. His concepts would be incorporated into Duhamel du Monceau's practical textbook of theoretical naval architecture, *Éléments de l'architecture navale* (Elements of Naval Architecture), a very popular work that rendered stability theory into workable practice (as will be discussed later in this chapter).

Theory into Practice

When Bouguer's *Traité du navire* was published in 1746, its impact was almost immediate; unlike many other developments in rational mechanics, stability theory found direct applications in the day-to-day practice of ship design. This occurred in two ways: first, by the increasing sophistication of calculations for weights, centers of gravity, and the metacenter within the design process; and, second, by the use of inclining experiments to validate stability. These applications were surprisingly widespread; most notably, stability theory was quickly incorporated at the insistence of naval administrators, among whom (as discussed in chapter 1) there was already a strong institutional development of scientific naval architecture, notably in the French, Danish, Swedish, and Spanish navies. Those navies were creating a system of professionalization that included schools of naval construction. The students, raised on stability theory, found it entirely natural to use it when they became constructors at the dockyards; and when they rose to positions of responsibility, they created the administrative systems that brought stability theory (and other theoretical developments) into the ship design process. This was not the case for the British, Dutch, and Venetian navies, which had provided little direct support for scientists working on ship theory. In particular, the British navy had already refined its bureaucracy and standardization of rates before 1720. Table 4.2 compares the evolution of stability-related information developed on ships' plans as a way of tracing that progress.¹⁰⁰

France

Although Blaise Ollivier had calculated the weights and displacement of *Fleurion* in 1729 and of a 64-gun ship in 1743, this practice did not become systematic until 1765. Duhamel du Monceau's first "Little Navy School" (1741–1758) provided the practical basis for students to learn the basics of displacement calculations and stability theory,

and his textbook *Éléments de l'architecture navale* extensively illustrated these calculations.

Duhamel du Monceau was also involved in developing the ordinance of 1765 under Minister of the Navy Choiseul (discussed in chapter 6), which formalized the data to be included on ships' plans: "centers of gravity and resistance, and height of the meta-center," as well accompanying calculations and a tabulation of hull materials.¹⁰¹ A senior constructor would check the calculations before they were submitted to the inspector general for approval.¹⁰² By this time, highly detailed lists of construction materials were being recorded at the French dockyards, which facilitated the ability of the constructors to carry out these tabulations.¹⁰³

The calculations that accompanied these plans showed a high degree of sophistication very early on, including estimation of hull weights by cubic ratio with a parent ship, and weight accounting by category of material (hull, armament, etc.).¹⁰⁴ For example, in 1763–1764 Antoine Grognard conducted a long series of studies for the 110-gun ship *Bretagne*. Minister of the Navy Choiseul had been unhappy with the performance of another recently constructed 110-gun ship, *Royal Louis* (discussed later in this chapter), and wanted assurance that *Bretagne*, though slightly smaller, would be superior. Grognard developed a weight estimate based on the older ship:¹⁰⁵

I found the hull of the *Royal Louis* weighed 2650 *tonneaux* . . . [and] as the weights of similar solids are in proportion to the cube of their dimensions . . . the new ship will be 2430 *tonneaux*, but as the Council demanded 4 *pouces* (1.7 centimeters) of hull thickness, longer nails and perhaps heavier wood than I estimate, the hull of the new vessel will displace at least 2500 *tonneaux*.

Grognard then provided a weight breakdown by group for the ship:

Recapitulation of Weights	<i>Tonneaux</i>
Hull	2500
Apparatus (pumps, boats, etc.)	370
Munitions (cannon + shot)	480
Provisions for six months	929
Repair parts	15
Officers and crew	116
<u>Ballast</u>	<u>700</u>
Total weight of hull and armament	5110

Later, the standardized plans introduced in 1786 by Duhamel's successor as inspector general of the navy, Jean-Charles de Borda, listed the specific immersion of the hull at full and light load in tonnes-per-centimeter equivalent (i.e., the number of tonnes required to increase draft by 1 centimeter), which allowed a rapid estimate of the effect of loading weights on the ship. The most difficult part of the calculation remained

Table 4.2

Comparison of stability-related information in design plans

	France	Spain	Denmark	Sweden	Britain	Netherlands	Venice
1700s	Length, beam, depth	Length, beam, depth Tonnage	Length, beam, depth Draft	Length, beam, depth	Length, beam, depth Tonnage	Length, beam, depth Tonnage	None
1710s	Length, beam, depth	Length, beam, depth Tonnage	Length, beam, depth Draft	Length, beam, depth	Length, beam, depth Tonnage	Length, beam, depth Tonnage	None
1720s	Length, beam, depth	Length, beam, depth Tonnage	Length, beam, depth Draft (fore/aft)	Length, beam, depth	Length, beam, depth Tonnage	Length, beam, depth Tonnage	None
1730s	Length, beam, depth	Length, beam, depth Tonnage	Length, beam, depth Draft (fore/aft)	Length, beam, depth Draft (<i>project</i>)	Length, beam, depth Tonnage	Length, beam, depth Tonnage	None
1740s	Length, beam, depth	Length, beam, depth Tonnage	Length, beam, depth Draft	Length, beam, depth Draft	Length, beam, depth Tonnage	Length, beam, depth Tonnage	Length, beam, depth
1750s	Length, beam, depth Tonnage	Length, beam, depth Tonnage Draft (fore/aft) Freeboard (gunports)	Length, beam, depth Draft Displacement	Length, beam, depth Draft	Length, beam, depth Tonnage	Length, beam, depth Tonnage	Length, beam, depth

1760s	Length, beam, depth	Length, beam, depth	Length, beam, depth	Length, beam, depth	Length, beam, depth	Length, beam, depth
	Draft	Draft	Draft	Draft	Draft	Draft
	Displacement	Displacement	Displacement	Displacement	Displacement	Displacement
	Center of buoyancy	Center of buoyancy	Center of buoyancy	Center of buoyancy	Center of buoyancy	Center of buoyancy
1770s	Metacenter	Metacenter	Metacenter	Metacenter	Metacenter	Metacenter
	Length, beam, depth	Length, beam, depth	Length, beam, depth	Length, beam, depth	Length, beam, depth	Length, beam, depth
	Draft (fore/aft)	Draft	Draft	Draft	Draft	Draft
	Displacement (fore/aft)	Displacement	Displacement	Displacement	Displacement	Displacement
1780s	Center of buoyancy	Center of buoyancy	Center of buoyancy	Center of buoyancy	Center of buoyancy	Center of buoyancy
	Metacenter	Metacenter	Metacenter	Metacenter	Metacenter	Metacenter
	Length, beam, depth	Length, beam, depth	Length, beam, depth	Length, beam, depth	Length, beam, depth	Length, beam, depth
	Tunnage	Tunnage	Tunnage	Tunnage	Tunnage	Tunnage
1790s	Draft (fore/aft)	Draft (fore/aft)	Draft	Draft	Draft	Draft
	Displacement (fore/aft)	Displacement (fore/aft)	Displacement (fore/aft)	Displacement (fore/aft)	Displacement (fore/aft)	Displacement (fore/aft)
	Tonnes per cm	Freeboard (gunports)	Tonnes per cm	Tonnes per cm	Tonnes per cm	Tonnes per cm
	Center of buoyancy	Center of buoyancy	Center of buoyancy	Center of buoyancy	Center of buoyancy	Center of buoyancy
1790s	Metacenter	Metacenter	Metacenter	Metacenter	Metacenter	Metacenter
	Length, beam, depth	Length, beam, depth	Length, beam, depth	Length, beam, depth	Length, beam, depth	Length, beam, depth
	Tunnage	Tunnage	Tunnage	Tunnage	Tunnage	Tunnage
	Draft (fore/aft)	Draft (fore/aft)	Draft	Draft	Draft	Draft
1790s	Block coefficient	Block coefficient	Block coefficient	Block coefficient	Block coefficient	Block coefficient
	Displacement (fore/aft)	Displacement (fore/aft)	Displacement (fore/aft)	Displacement (fore/aft)	Displacement (fore/aft)	Displacement (fore/aft)
	Tonnes per cm	Freeboard (gunports)	Tonnes per cm	Tonnes per cm	Tonnes per cm	Tonnes per cm
	Center of buoyancy	Center of buoyancy	Center of buoyancy	Center of buoyancy	Center of buoyancy	Center of buoyancy
1790s	Metacenter	Metacenter	Metacenter	Metacenter	Metacenter	Metacenter
	Length, beam, depth	Length, beam, depth	Length, beam, depth	Length, beam, depth	Length, beam, depth	Length, beam, depth
	Tunnage	Tunnage	Tunnage	Tunnage	Tunnage	Tunnage
	Draft (fore/aft)	Draft (fore/aft)	Draft	Draft	Draft	Draft

the estimate of the center of gravity; most ship plans, even through the mid-1800s, listed only the height of metacenter above the center of buoyancy ($\overline{BM}$) but not the more critical height above the center of gravity ($\overline{GM}$), even given the minute details of materials available from the construction estimates. One young constructor, Jean-Denis Chevillard, pointed out to Duhamel du Monceau that he generally evaluated stability by comparison with other ships, and that he took measurements of centers of gravity of the parts of the ship only during the construction itself, pointing out that the calculation was very long, “during which it is difficult not to make mistakes.”¹⁰⁶

Mistakes were certainly all too common, and perhaps inevitable. In 1778 the minister of the navy, Pierre-Étienne Bourgeois de Boynes, ordered a hasty buildup of the French fleet following several years of stagnation and the entry of France into the War of American Independence. Ships were ordered, designed, laid down, and launched all within the same year. Perhaps due to this enforced haste, François Guilleme Clairin-Deslauriers, now chief constructor at Rochefort, made an “unpardonable error in calculation” in three 74-gun ships, *Pluton*, *Hercule*, and *Scipion*. He estimated their displacement at 2,878 tonnes with 1.7 meters of freeboard to the battery; on launch he discovered that the hull of *Pluton* weighed 1,485 tonnes instead of the 1,369 tonnes he had estimated, which brought the freeboard down by almost half a meter.¹⁰⁷ The ships’ lack of stability was evident from the start, so the Council of the Marine ordered a succession of stability trials. New ballast plans, loading conditions, and finally hull doubling were tried out on the *Scipion*, and the effect of each was recorded by measuring the heel angle from the guns being run out port and starboard. These experiments were recorded in *L’Art de la marine* (Naval Art) by Nicolas Charles Romme, professor of mathematics for the Naval Guard in Rochefort. Although these were not actual inclining experiments designed to calculate the position of the metacenter, they appear to be the first systematic stability trials ever published, and were widely quoted in other naval architecture texts.¹⁰⁸

Stability trials, involving the shifting of guns or men on deck to observe the effect on heel and roll (nowadays called “sallying”), had been around in one form or another since at least the time of the *Vasa*.¹⁰⁹ In France, “Borda’s rule” (named for the inspector of naval construction, Jean-Charles de Borda) was used to evaluate stability from about 1783 onward. This involved lining up a specific number of men on each side of the ship and measuring the difference in drafts port and starboard due to heel.¹¹⁰ These trials all gave useful, but ultimately subjective, information because they could not define the degree to which a ship was stable or unstable. For that, one needed the inclining experiment.

The first recorded inclining experiment took place in 1748, just two years after Bouguer published his work. Clairin-Deslauriers, at that time a junior constructor at Brest, performed the experiment on the newly built 74-gun *Intrépide*, apparently out of curiosity to test the new theory. He hung two 24-pound cannons from a buttress built on the side of the ship (figure 4.23), and although the buttress broke, he was able to take enough measurements to ascertain that the ship's GM was 1.8 meters.¹¹¹

The inclining experiment proved to be a practical tool for solving problems. In late 1762 the intendant of Brest, Aymar-Joseph, count of Roquefeuil-Kerlouet, ordered the inclining of the 110-gun *Royal Louis*, recently returned from a campaign in Brazil and the West Indies, to find out whether the ship was inherently unstable or not. The ship had sailed poorly from the start, and on 10 November 1762 almost capsized. Navy Minister Choiseul sent the astronomer Pierre-Charles Le Monnier to Brest in January 1763 to observe and participate in the experiments.

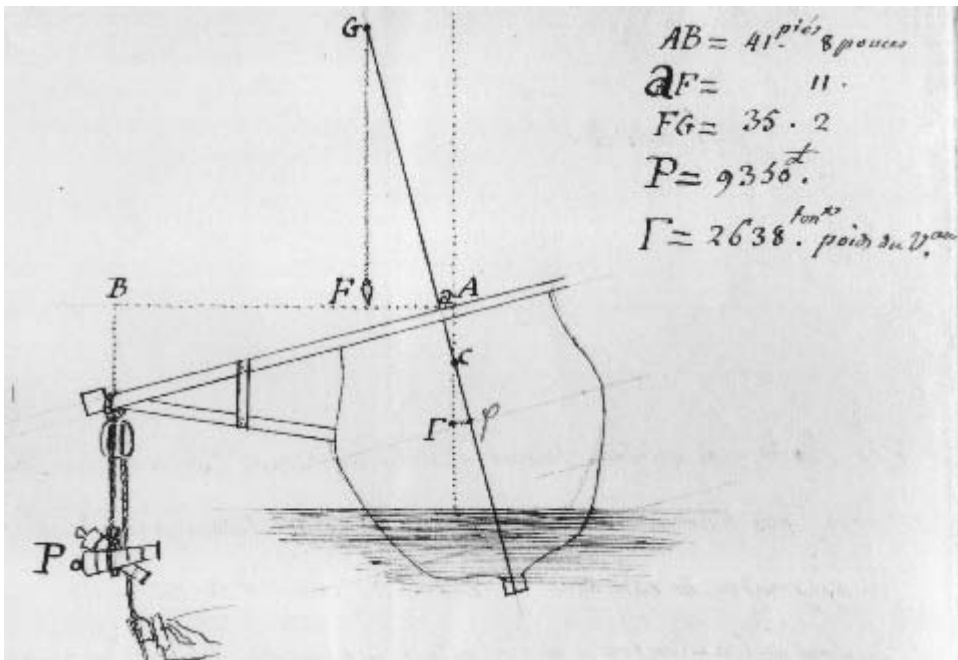


Figure 4.23

Inclining experiment on *Intrépide* by Clairin-Deslauriers (1748). (Clairin-Deslauriers, letter to Duhamel du Monceau, 1748). Credit: Phillips Library, Peabody-Essex Museum.

Le Monnier sent back a fascinating series of letters stating that the inclining experiment was “known by mechanics” (i.e., mathematicians) and crediting Roquefeuil with being “well-versed in the theory” of stability.¹¹² (Roquefeuil, as noted in chapter 3, was a strong advocate of research in ship theory, sponsoring Jean-Charles de Borda’s fluid resistance experiments at roughly the time these inclinings took place.) The inclinings and subsequent calculations, which evidently took six to seven weeks to complete, showed the $\overline{GM}$ of the ship to be about 1.3 meters, which Le Monnier considered acceptable (it wasn’t; most ships of that size had a $\overline{GM}$ of around 1.7 to 2.0 meters), although he recommended that the ship be given shorter masts and yardarms. Despite this endorsement of *Royal Louis*’s stability, it rotted at pierside until its demolition in 1772. The inclining experiment itself may also have fallen into disuse after that; the facts that the *Scipion* was not inclined in 1778, and that Borda’s rule was used after 1783, point to at least a temporary return by constructors to subjective measurements.

Spain

It is perhaps surprising that stability theory was not routinely used in the Spanish navy until the 1780s, given that one of the most important figures in the history of naval architecture, Jorge Juan y Santacilia, was both well acquainted with stability theory and in charge of naval construction from 1752 to 1754. As described in the prologue, Juan y Santacilia had traversed the Andes with Bouguer as a young lieutenant, and may have learned about the metacenter directly from Bouguer even before the latter had finished his manuscript. He had since kept abreast of developments in ship theory, corresponding with the academies of Paris, Berlin, and Saint Petersburg, and by 1752 was writing *Examen marítimo* (Maritime Examination), in which he greatly expounded on stability theory and provided real-life examples of stability calculations. Juan y Santacilia, as head of the Council of Constructors that established construction standards, was in a position to institutionalize stability theory in the design process; and as head of the Navy Guards, he had authority over the officers who would oversee the dockyards. So why did the metacenter not appear on Spanish ship plans until so late?

One possible answer may lie in the letter Juan y Santacilia wrote in 1766 to his colleague José Romero Fernández de Landa, critical of theoretical naval architecture in general (also discussed in chapters 1 and 3):

The calculation to find out the volume that the Ship occupies under the water is the only thing that Bouguer and Duhamel have brought with certainty; but it is also older than their grandfathers; all the rest are false . . . even the Metacenter which serves to determine the support for the Sail, because [the calculations] lack the details that are needed.¹¹³

Jorge Juan saw, probably more clearly than his contemporaries, that the basic geometrical calculations then in use provided only the height of the metacenter above the center of buoyancy ($\overline{BM}$), but that was effectively meaningless without also knowing the height above the center of gravity ($\overline{GM}$), and that calculation was too laborious for almost any constructor.

Nonetheless, that calculation was part of the new French standardization that Jean-François Gautier was tasked to bring to Spanish naval construction; as discussed in chapter 1, Gautier was called to Spain in 1765 to oversee the alignment of the Spanish navy with the French, and to begin the process of professionalization of constructors. The Navy Ordinance of 1776, like Choiseul's 1765 ordinance, established the technical information required to be included on ship plans, including displacement and stability calculations. In the pattern of other countries, as students became working constructors, stability calculations began showing up on plans. Ironically, it was Juan y Santacilia's *Examen marítimo*, the standard textbook of the Spain's Corps of Naval Engineers, which would guide them through the process, despite the author's own cynicism about the utility of the theory.

Denmark

The metacentric theory of stability began to be incorporated by the Danish navy in the 1770s. This was due principally to two factors. The first was the widespread distribution of Duhamel du Monceau's second edition (1758) of *Elémens de l'architecture navale*, which contained step-by-step instructions for stability calculations; many navies, including Denmark's, obtained copies of *Elémens* as the de facto textbook of naval construction. The second factor was the extensive training abroad that Danish constructors undertook, sometimes working and studying for years before returning to their homeland (as will be discussed in chapter 6). For example, Frederik Wegersløff had met Euler in Saint Petersburg in 1734, and subsequently corresponded with him about stability during his tenure at the Naval Cadets Academy; Frederik Michael Krabbe met Duhamel du Monceau and Bouguer during his trip to France in 1754; and Frantz Hohlenberg studied under the Swedish constructor Fredrik Henrik af Chapman in the 1790s.

Sweden

It is no exaggeration to state that Fredrik Henrik af Chapman single-handedly introduced naval architecture theory into Swedish naval construction. Designs by Charles Sheldon and William Smith, two constructors from the late 1600s, showed no indication of displacement calculations from 1700 to 1730. Although Admiral Thomas

von Rajalin had introduced displacement calculations on a 50-gun ship project in 1730, that had not been repeated. In the 1740s, the constructor Gilbert Sheldon, one of Rajalin's protégés and son of Charles Sheldon, presented papers before the Royal Swedish Academy on the use of scale models to determine a ship's displacement and center of buoyancy.¹¹⁴ Although he evidently developed some rules based on these experiments for the position of the midship frame, none of his ship plans show any evidence of displacement calculations. Another constructor, Harald Sohlberg, apparently did carry out some displacement calculations around 1747, but this evidence comes from discussions with the Admiralty Board and does not appear on his ships' plans.¹¹⁵

As part of a study tour abroad from 1750 to 1757, Chapman lived for a while in Britain to learn shipbuilding techniques and to study mathematics under Thomas Simpson, a professor at the Royal Military Academy in Woolwich, near London. As a civilian and a foreigner, Chapman would have been prohibited from taking classes there, so he was tutored on the side.¹¹⁶ Chapman learned what would become known as "Simpson's rule," a numerical approximation of the integral of a function, using at least three equally spaced points for measurement (figure 4.24).¹¹⁷

After further visits to France and Holland, and buying several books on ship theory,¹¹⁸ Chapman returned to Sweden in 1757 to continue his career as a constructor. In this process he soon made it his habit to calculate a ship's displacement and metacenter as a function of draft, applying Simpson's rule for numerical integration.¹¹⁹ His methods of calculating ship stability became well known internationally through the popularity of his works *Architectura Navalis Mercatoria* (Merchant Naval Architecture) and *Tractat on skepps-byggeriet* (Treatise on Shipbuilding). Chapman helped to promulgate the use of the metacenter and to make its calculation a routine matter among naval architects. At the same time Simpson's rule, which offers certain efficiency advantages over the trapezoidal rule for an equal number of intervals, was popularized, and is still much favored today.

By 1782 Chapman had become the de facto chief constructor for the Swedish navy. His rise to power was due as much to his political connections with the "Hats" party and the king as it was to his reputation as a "scientific" ship designer when compared with his predecessor and rival Gilbert Sheldon.¹²⁰ Chapman's design methods, including the formalized calculations of stability, therefore became the de facto standard for the Swedish navy. Even after his retirement, his establishment of the Fleets Constructor Corps ensured that future Swedish constructors would carry on the use of ship theory in their design of ships.

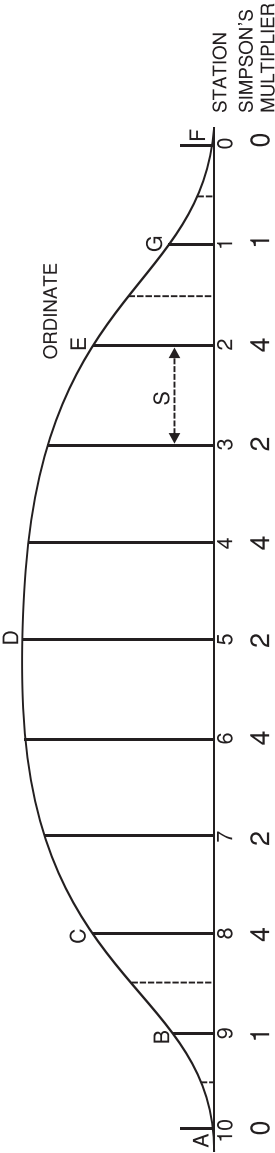


Figure 4.24
Simpson's rule. Area = $\frac{1}{3}S \times \Sigma$ (ordinate $\times$ Simpson's multiplier).

Britain and the Netherlands

The two nations that shared an institutional cynicism toward theory also developed a strong shipbuilding link, as the Amsterdam naval dockyard was overseen from the 1720s by a succession of British constructors (but they were in continuous competition with Dutch-born constructors in the Rotterdam dockyard). Although both Anthony Deane and Johann Hudde had demonstrated the methods for calculating displacement, no ships' plans in either country showed that calculation being made. Likewise, although the British constructor Mungo Murray had translated Bouguer and Duhamel du Monceau into English as early as 1754, with a considerable number of copies sold,¹²¹ no plans of British warships contained stability information until well into the 1860s.¹²²

The British navy was well aware of stability experiments. In 1762 the Society of Arts in London had included in its trials of model naval ships (discussed in chapter 3) several measurements of the models' resistance to heel, but these were qualitative only.¹²³ The navy itself conducted at least one set of inclining experiments involving several warships. By order of Rear Admiral John Leveson-Gower, the 98-gun ships *Formidable* (his flagship) and *Barfleur*, as well as the 74-gun *Bombay Castle*, were inclined, probably sometime between 1787 and 1790. The results were later reported anonymously to the Society for the Improvement of Naval Architecture. The inclinations were made by first running out the cannons, and then further heeled by calling the crew to quarters at the ship's sides. The calculations showed that the 98-gun ships had a $\overline{GM}$ of about 1.0–1.2 meters, while the $\overline{GM}$ for the 74-gun ship was about 1.3 meters.¹²⁴

In the Netherlands, *Éléments de l'architecture navale* was translated into Dutch in 1757, but no Dutch plans contained stability information until the 1800s. The sole exception to this was the inclusion of the metacenter in the plan for the 12-gun corvette *Lynx*, built in 1784; its designer, G. J. Palthe, was not a constructor, but had taught himself Chapman's methods and was invited by the Amsterdam Admiralty to build a corvette using this knowledge. It is perhaps telling that the experiment was not repeated.¹²⁵

As stated earlier, both the British and the Dutch navies had undergone a system of standardization well before naval architecture theory came into the picture; the British bureaucracy had changed little since the Establishment of 1719, and the Dutch dockyards at Rotterdam and Amsterdam, although often at bureaucratic odds, had each developed more or less standard systems in the 1720s. The Dutch Admiralty would not use stability theory until the early 1800s, when a generation of its constructors

was trained in the French School of Engineer-Constructors of the Navy during Napoleon's rule of the Kingdom of the Netherlands. In Britain, the same pattern applied; only when the constructors graduated from the first schools of naval architecture and rose to power in the 1860s (as discussed in chapter 6) did metacentric calculations become routine.

Venice

The paucity of ships' plans that survived Napoleon's invasion and destruction of the Arsenale in 1797 make it difficult to accurately determine the extent to which Venetian constructors were employing stability theory. It appears that few plans before 1740 contained even basic construction information, perhaps serving more as guides than as sets of "build-to-print" drawings. In the 1760s the 64-gun *San Carlo Borromeo* was the subject of numerous studies by the hydraulics engineer Giovanni Poleni, as the Venetian navy decided to adopt it as the standard type for all first-rate ships, and it appears that he performed at least the basic displacement calculations.¹²⁶ However, there is no indication of further use of stability theory until the 1800s. Part of the reason for this absence of calculations is the rather late and short-lived existence of a school of naval architecture, which opened in 1777 and closed during the French invasion of 1797.¹²⁷

The Impact of the Metacenter Until 1800

Ultimately, the invention of the metacenter did not have any practical effect on ship design during the 1700s. To demonstrate this, a progression of length-to-beam ratios of French ships from three periods is shown in table 4.3, with a "baseline" of British ships shown as a comparison.

In France, ships did not become uniformly broader or narrower as a result of stability calculations coming into use; the comparison with Britain demonstrates that there was a general variation over time in hull form that was the result of other factors. The arrival of stability calculations did not, of course, suddenly reveal any significant weaknesses in design that had gone unnoticed before; but it did allow constructors to create new designs with greater confidence.

Extensions of Stability Theory

The impacts of Bouguer's *Traité du navire* and Euler's *Scientia Navalis* were felt within the European scientific community even before their publication. The invention of

Table 4.3

Length-to-beam ratios of French and British ships

FRANCE			
Rate (guns)	1745 pre-stability calculations	1760 emerging stability calculations	1786 institutionalized stability calculations
110	3.64	3.60	3.74
80	3.80	3.64	3.75
74	3.83	3.81	3.82
64	3.73	3.80	3.80
BRITAIN (no stability calculations)			
Rate (guns)	1717	1760	1788
100	3.48	3.47	3.97
90/98	3.47	3.58	3.97
70/74	3.63	3.54	3.59
60/64	3.69	3.53	3.59

Sources: Villiers, *La Marine de Louis XVI* (1985), list of plans; Fincham, *A History of Naval Architecture* (1851/1979), pp. 83, 103, and 177.

the metacenter opened up several new avenues of research: oscillation of floating bodies; the application of the metacenter to longitudinal stability; and the development of stability theory at large angles of heel. The problems of oscillations were the first to be addressed.¹²⁸

Heave, Roll, and Pitch

Euler had evidently been thinking about oscillations ever since he critiqued the work of La Croix in 1735–1736. In an exchange of letters from 1737 to 1738 with his former teacher Johann Bernoulli, he described his nascent theory of stability for any arbitrary body, and also proposed a way to determine the frequency of oscillation around the stable position. Originally, Euler had considered only rotating oscillations (roll/pitch), but Johann reminded him that a body will also oscillate vertically (heave). Johann's son Daniel, by then in Berlin, had been reading the correspondence and began “ruminating” (his word) about stability and dynamics; his first memoir on the stability of floating bodies was read by Euler to the Saint Petersburg Academy of Sciences in late 1738, and his second memoir on oscillations was read a year later. In the first memoir he developed a theory of stability based on torque and minimum energy, and derived formulas for cylinders and cubes (though he specifically avoided deriving rules for

ships), with results similar to those already developed by Euler. Of particular interest is that in this memoir, Daniel Bernoulli mathematically defined, for the first time, heave, roll, and pitch (figure 4.25) as the three degrees of freedom of a floating body.¹²⁹

The second memoir built on the first and introduced properties of inertia and vibration that Daniel Bernoulli had developed separately. It was a short memoir, concerned only with small oscillations of simple shapes (rod, disk) in still water, and used analogies to an equivalent pendulum, which was the common means of modeling oscillations at the time; mathematicians were still at the beginning of their investigations into dynamics and had not yet developed more complex tools.¹³⁰ Although he did not specifically address ships, Bernoulli noted that his conclusion that the wider the water plane (i.e., the beam of the ship), the shorter the period of oscillation “conforms to the laws of naval architecture.”¹³¹ Through a series of delays by the Saint Petersburg Academy, the memoirs were not actually published until 1747 and 1750, respectively, well after the works of Bouguer and Euler had already appeared, and thus went virtually unnoticed by the scientific community. Daniel Bernoulli would not return to the subject for almost 20 years.¹³²

Bouguer, unaware of Daniel Bernoulli’s work,¹³³ treated the theory of oscillations in *Traité du navire* in a rather perfunctory manner, addressing only rolling. Unlike Bernoulli, Bouguer developed a generalized set of equations for modeling the ship as an equivalent pendulum by taking into account the second moment of inertia (the sum of the masses of the body times the square of their distance from the center of

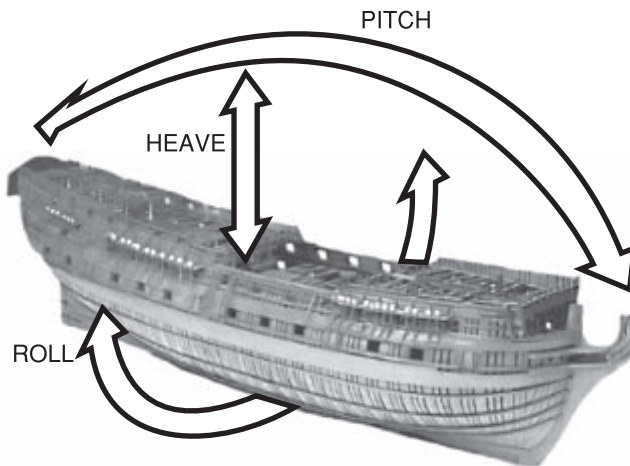


Figure 4.25
Heave, roll, and pitch.

gravity) as the means of determining the period of roll (τ_0). In modern terms, the equation was

$$\tau_0 = \frac{\int mr^2}{\Delta GM},$$

where m is a point mass and r is the distance of the mass from the center of gravity; in effect, this is the ratio of the radius of gyration (elucidated in 1703 by Jacob Bernoulli) to the metacentric height. Bouguer had evidently carried out some experiments on roll during his return from Peru, for he referred to the *Triton* (the slave ship he returned on) as being fairly stiff, having a roll period of 4.5 seconds.¹³⁴ The practical application of these experiments and theories was to determine the change in roll period due to an increase in the weight of masts.¹³⁵

A decade later, Bouguer came back to the subject in an Academy of Sciences memoir and in his second book on naval architecture, *De la Manoeuvre des vaisseaux* (On the Maneuvering of Vessels). The memoir presented a solution for combined roll and heave, which extended the equation given above to model, in effect, a double-balance pendulum.¹³⁶ The book provided a longer solution to the same problem, and addressed the effect of moment of inertia on pitch and roll.¹³⁷ In particular, Bouguer argued that by decreasing the mass of the ship at the bow and the stern, the pitch period becomes shorter and the pitch amplitude and speed become greater. He therefore recommended that the ends of the ship be made heavier.

Euler, in his *Scientia Navalis*, provided a lengthy explanation of isochronous oscillations in pendulums, which served as the basis for his subsequent determination of the equivalent length of pendulum to define rolling and pitching.¹³⁸ In Euler's equation, this length,

$$l = \frac{r^2}{GM},$$

where (as above) r is the distance of the mass from the center of gravity; in effect, he arrived at the same equation as Bouguer, but by dividing out the integral of the point masses by the displacement. Euler also treated oscillations in oblique planes as well as combined with vertical oscillations. However, he was unable to provide an explanation of ship motions in waves, lamenting that "theory abandons us entirely."¹³⁹

Jean Le Rond d'Alembert, who first developed the concept of pressure to explain fluid resistance in his *Essai d'une nouvelle théorie de la résistance des fluides* (Essay on a New Theory of the Resistance of Fluids), attempted to use the same principles in developing a theory of oscillations of a floating body. He did not get very far, eventually falling back to an equivalent-pendulum approach. D'Alembert did introduce a formula

originally developed for the precession of the equinoxes to model the precession of a floating body; but evidently this concept was never pursued further.¹⁴⁰

The French Academy of Sciences considered the subject of rolling and pitching so vital that it proposed the issue three times in succession for the Rouillé de Meslay Prize—1755, 1757, and 1759. The selection committee in all three years consisted of notables such as Bouguer, Alexis de Clairaut, and Pierre-Charles Le Monnier. The prize for the first year was awarded to the memoir by M. Chauchot, an assistant constructor at Brest, over that of Antoine Groignard, then chief constructor at Rochefort (his memoir is discussed later).¹⁴¹ Chauchot's memoir was very subjective, with a few unsatisfactory equations (e.g., calculating static angles of roll, instead of roll periods), and addressed the best hull shape to reduce the forces of roll and pitch. On the subject of roll, he proposed that ships be given a trapezoidal cross section, a small metacentric height, and a false keel in order to reduce and dampen roll motions.¹⁴² On the subject of pitching, he recommended that, to reduce the "shock" of pitching, the bow and stern be identical and completely vertical (based on his observations of fishing boats), and of constant shape from keel to deck.

Chauchot's memoir was immediately approved for publication, though posthumously.¹⁴³ However, the Academy agreed that the issue needed to be examined in more depth, and posed the same question for the 1757 prize.¹⁴⁴ Daniel Bernoulli now returned to the subject he had left 20 years earlier, and was immediately faced with a dilemma: Should he refer to his earlier work or derive his ideas anew? He knew that Bouguer was on the committee, and probably thought it best not to remind Bouguer of his precedence in the theory of rolling; moreover, any self-reference would have affected the enforced anonymity of the entrants.¹⁴⁵ Bernoulli therefore repeated the derivation from his previous two papers, but in a much wordier and less mathematical way. The resulting memoir was actually two different papers; the first half treated oscillations in still water, and the second dealt with forced oscillations—essentially, treating ships in waves for the first time.¹⁴⁶ In the first half, he treated idealized hulls with rectangular and round shapes, showing, for example, that the "momentum of force" (i.e., righting moment) for a rectangle is three times that for a circular section at large angles of roll. His formula for the natural period (τ_0) of the ship was based on the inertia (I) and righting moment (RM) of the body:

$$\tau_0 = 2\pi \sqrt{\frac{I}{RM}}.$$

In the second half, Bernoulli developed the model of wave-induced rolling, modeling a series of "shocks" induced by an outside force (presumably breaking waves) on the ship in the same manner as rhythmically striking a swinging pendulum; he

noted that when the frequency of the shocks τ approaches τ_0 , resonance will cause problems.¹⁴⁷ He also analyzed the angle of heel of a ship on a swell, arguing that the torque would tend to make the ship heel at more than double the angle of the sloping wave.

Bernoulli went beyond the specifications of the Academy by examining wind-driven surface waves (using oscillating water columns as the model) and the effect of wave pressure on the hull; these predated more complex applications by almost a century.¹⁴⁸ However, he neglected to address one of the key concerns of the Academy, the problem of pitching.¹⁴⁹

That concern was taken up in 1759 by the Academy, which again proposed a prize on the subject of rolling and pitching, but worded it in such a way—"examine the forces sustained by all the parts of the vessel"—that the entrants had to take a hard look at pitching, which was the most damaging of ship movements. The two entrants who ended up sharing the prize of 2,000 *livres tournois* (around \$13,600 in 2002), Leonhard Euler and Antoine Groignard, produced widely different memoirs on the subject, each according to his career.¹⁵⁰ The mathematician Euler developed a methodic examination of force in four parts: static forces at rest (e.g., due to the pull of mast stays); direct force of the "shock" of water while in motion; centrifugal forces due to rolling; and centrifugal forces due to pitch.¹⁵¹ His principal conclusion was precisely opposite to that of Chauchot, and quite ahead of its time; Euler proposed flaring the bow outward to slow down the pitching motion (and force) before submerging the main deck. In modern terms, bow flare adds to the water plane as the bow descends, acting like a spring to brake the rate of descent.

The constructor Groignard simply reprised his 1755 memoir, taking a practical approach to the problem and proposing structural improvements to strengthen the ship against pitch and roll.¹⁵² Groignard suggested that the bow structure be stiffened diagonally to better resist the "shock" of the water, and that the frames be thinner, more numerous, and more closely spaced to reduce the bending of the ship. He introduced no theory, equations, or even numbers to support his conclusions; nonetheless, the proposed improvements (they were never actually built) anticipated those developed by the British constructor Robert Seppings some 50 years later.¹⁵³

The Academy proposed prizes in 1761 and 1765 for a related subject, the lading and ballasting of ships. The 1761 prize was taken by Johann Albrecht (Jean-Albert) Euler, Leonhard Euler's eldest son, over the essay of the French mathematician Charles Bossut.¹⁵⁴ Euler's memoir argued that stowage should be brought close to the longitudinal center of the ship to reduce the yaw moment of inertia (less effort for the rudder and easier steering), yet kept either very high or very low in the ship (i.e., far

from the axis of rotation) to reduce pitching. The 1765 prize was sought by Bossut (reprising his 1761 memoir), two naval constructors (Antoine Groignard and Jean-François Gautier, just before the latter's transfer to Spain), and an East Indies Company officer (Jacques Bourd  de Villehuet).¹⁵⁵ The prize was awarded for Bossut's memoir, which examined structural strength due to static loads and also developed lengthy equations to determine the angles of roll and pitch. Bossut's conclusion was that roll could be reduced by placing stowage as near to the center of buoyancy as possible. The other authors came to different conclusions; for example, Groignard and Bourd  de Villehuet argued that the weight of stowage at each horizontal slice of the ship should match the displacement of the slice. Of course, with such contradictory advice coming from each author, it would have been impossible to develop a set of rules on lading and ballasting.¹⁵⁶ Moreover, almost all the suggestions neglected the very practical difficulties in arranging ballast, victuals, and ammunition for loading, unloading, and ease of access when required.

The Spanish constructor Jorge Juan y Santacilia carried out the last systematic examination of rolling and pitching before the seminal research of the British scientists Henry Moseley and William Froude a century later. Although Juan y Santacilia acknowledged the work done on oscillations by Bouguer and Euler, he did not know of Bernoulli's 1757 prize memoir (published in 1771, the same year as his own *Examen mar timo*), so it is not surprising that he independently covered the same ground as Bernoulli, although he came to different conclusions. For example, he developed a fairly complex equation for rolling that accounted for fluid resistance, but as this was considered insignificant, his equation for roll period devolved to

$$\tau_0 = \frac{(\text{Radius of gyration})}{\sqrt{GM} \times l},$$

where l = the length of a pendulum of 1 second.¹⁵⁷

The length of a pendulum of 1 second is g/π^2 ; substituting units, this gives

$$\tau_0 = \frac{\pi \times (\text{Radius of gyration})}{\sqrt{GM} \times g}.$$

This is, in essence, the same formula used today for unresisted rolling¹⁵⁸:

$$\tau_0 = \frac{\text{constant} \times (\text{Radius of gyration})}{\sqrt{GM}}.$$

Juan y Santacilia also developed a geometrical means of evaluating the roll in waves, in order to account for waves of varying periods; he also added terms to his equations to account for the effects of sails (e.g., increasing roll period from five seconds to six seconds for a 60-gun ship).

In studying pitch, Juan y Santacilia also examined the effect of what today is termed “encounter frequency” (i.e., the period at which a moving ship encounters wave crests). He concluded that in head seas, it was advantageous to slow down in order to reduce pitch period. He further concluded that the hull should have wide sections at the bow, and increase in section moving upward from keel to deck, in order to diminish and cushion the pitch motions.¹⁵⁹

Longitudinal Metacenter

Almost as an aside, Juan y Santacilia elaborated upon a second important extension of stability theory, the calculation of the longitudinal metacenter of a ship. Although both Bouguer and Euler had noted the existence of this metacenter, Juan pointed out that the longitudinal metacenter ($\overline{GM}_L$) is an order of magnitude greater than the transverse metacenter, and used it in estimating pitch motions.¹⁶⁰

Large Angles of Heel

The third extension of stability theory, and arguably the most substantial since Bouguer’s original work, occurred not on the European continent but in Britain.¹⁶¹ In

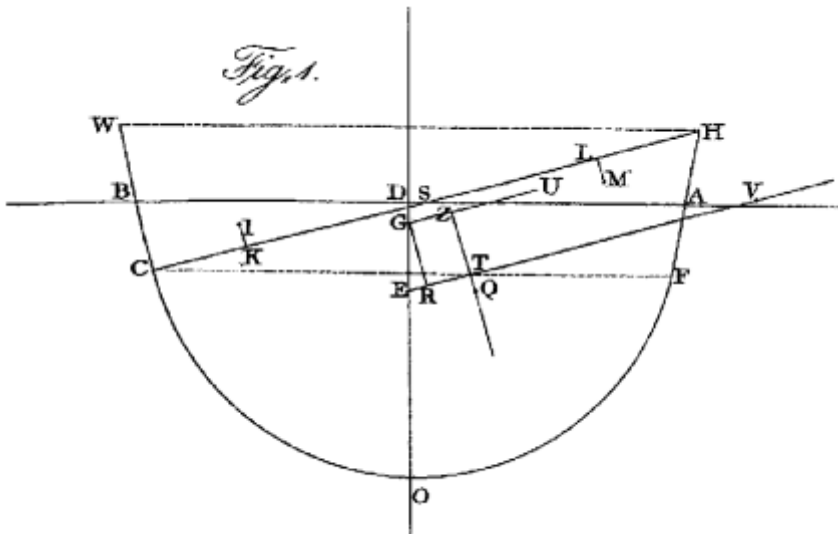


Figure 4.26

The GZ curve as explained by Atwood and Vial du Clairbois. (Atwood and Vial du Clairbois, “A Disquisition on the Stability of Ships” [1798], fig. 1). Credit: Bibliothèque Nationale de France/Gallica.

two papers presented to the Royal Society of London, the British mathematician George Atwood (assisted by the French constructor Honoré-Sébastien Vial du Clairbois) examined the inclination of ships at large angles of heel.¹⁶² The first paper was little more than a recapitulation of theory by Bouguer, Euler, and others, with a thorough examination of bodies in equilibrium—stable, unstable, and neutral—through 360 degrees of rotation, in effect, taking into account the complete form of a body and not just its water plane. Atwood took care not to limit his analysis to floating bodies, but applied his results to any body subject to external forces. He critiqued the various methods used for calculating areas, including those of Newton, Bouguer, Simpson, and James Stirling, and pointed out that a ship's rolling is not isochronal like that of a pendulum, but is in fact variable because it rotates through a large arc with unequal legs.

The second paper built on the first, and for the first time provided a numerical analysis of the righting moment of a ship at specific angles of heel. Atwood and Vial du Clairbois proposed the term GZ to define the righting arm, at first for simple cross sections (see figure 4.26 for an example) and prismatic shapes, then for an actual ship; both the term and the concept are used to this day. They derived the GZ of simple shapes by trigonometric analysis in closed form, and discussed the characteristics of different section shapes. Atwood and Vial du Clairbois made the observation several times that the theory of the metacenter does not provide a complete picture of stability, but only explains it over a very small range of heel from the vertical, and thus initial stability alone is insufficient as a criteria for overall stability.¹⁶³

By 1800, a more complete picture of stability was being built, accompanied by other improvements in naval architecture, such as experimental research into hydrodynamics, but most of the subsequent development and application would be done not by scientists under the aegis of government-sponsored scientific academies, but by engineers attempting to solve specific problems as they were building ships.

5 The Great Works

By 1700, only two books of naval architecture had been published, both in French. By 1800, almost three dozen books were in print in at least eight languages, including various translations. Many of these books treated single subjects in some detail (e.g., maneuvering), but from early on, the works of *synthesis* were more influential, treating the entire discipline—including hull geometry, stability, and hydrodynamics—as a whole. This chapter explores six of the great works of synthesis in naval architecture that appeared before 1800, chosen for the impact they made upon the fledgling profession. Four of them were original works of theory which established important concepts that underpinned the new, “rational” view of ship design. Two served as textbooks for a new generation of constructors and had the widest appeal because they distilled the important parts of other works and often reduced complex equations to simple rote arithmetic. Taken together, these six works defined the shape and structure of naval architecture for well over a century.

Paul Hoste, *Théorie de la construction des vaisseaux* (1697)

Paul Hoste was a Jesuit mathematics professor at the School of Navy Guards in Toulon, when he wrote the first attempt at a synthesis of naval architecture, *Théorie de la construction des vaisseaux* (Theory of the Construction of Vessels, figure 5.1). The history of its publication goes back quite a bit farther. Soon after Hoste was appointed to the School in 1685, he met the French admiral Anne-Hilarion de Cotentin, count of Tourville, with whom he would work closely for the rest of his life. Hoste and Tourville had differing ideas on the theory of ship construction, Tourville favoring classical ship designs, whereas Hoste preferred a mathematically based approach. In early 1686, while in Toulon, Tourville tested a large model of a conventional ship (*Hasardeux*) against a smaller one, built to Hoste’s ideas, which included a hemispherical bow and stern. Hoste’s model did not perform well, and Hoste temporarily laid aside his

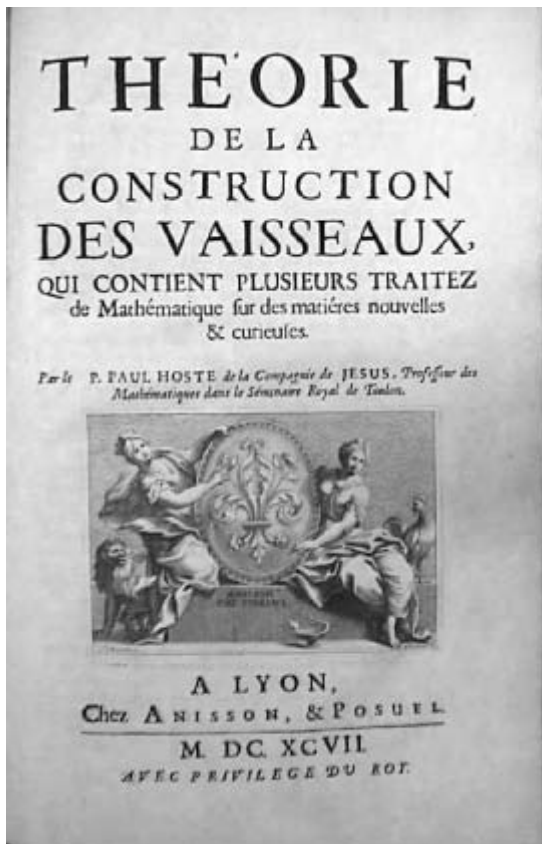


Figure 5.1

Paul Hoste, *Théorie de la construction des vaisseaux* (1697). Credit: U.S. Navy Historical Center.

research into ship construction.¹ Nevertheless, Tourville was impressed with Hoste's capabilities, and Hoste served him as chaplain on several campaigns, including the battle of La Hogue in 1692. Hoste later collaborated with Tourville on *L'Art des armées navales* (The Art of Naval Armies), a magnificent 400-page book that described the major naval battles over the previous century and developed carefully argued, geometrically analyzed reasons for specific tactics and maneuvers based on Tourville's ideas. The book, the first major work on naval tactics, was reprinted several times and translated into Danish, Swedish, and English, thereby influencing tactical thinking in Europe and the Americas for over a century.

Somewhat incongruously, appended to this book was the smaller work *Théorie de la construction des vaisseaux*, which Hoste stated was written at the "express order" of

Tourville,² even though Tourville knew that Hoste's earlier experiments showed his ideas were flawed. The two books were published in October 1697 at Lyon by Anisson (a family dynasty in the Lyon printing industry) and Jean Posuel. It was a large work, about 36 by 23 centimeters, and quite heavy—550 pages in *L'Art* and 180 pages in *Théorie*, a total of over 700 pages. The two books together were something of a "best-seller," due to the interest in *L'Art des armées navales* and not to the work on ship theory.

In the preface, Hoste explained his reasons for writing *Théorie de la construction*, arguing that constructors did not start with the necessary principles before determining the measurements of a vessel, making the now-famous claim: "The Constructors today do as did the old ones, and *they do not yet know what the sea wants*."³

Hoste therefore used mathematical theory to determine "*what the sea wants*," in order to provide some rules. The book reads like a mathematics textbook instead of a treatise on ship construction, containing "propositions," "corollaries," and "demonstrations." The mathematics and terminologies are not explained well and are difficult to follow, especially given their Aristotelian heritage that is unfamiliar today; in some cases the math is quite simply wrong.

Hoste divided *Théorie de la construction des vaisseaux* into three books, as follows:

Book 1 On the figure of the vessel in general

Chapter 1 On the figure of the vessel in relation to the water it must divide

Chapter 2 On the figure of the vessel in relation to the sail it must carry

Chapter 3 On the figure of the vessel in relation to pitching

Chapter 4 On the figure of the vessel in relation to the dérive

Chapter 5 On the figure of the vessel in relation to the rudder

Book 2 On the solidity of vessels

Chapter 1 On the strength of the parts that compose the vessel

Chapter 2 On the strength of the joints of the parts of the vessel

Chapter 3 On the force that the parts of the vessel must support

Chapter 4 On the manner in which the parts of the vessel support themselves

Book 3 On the plans of vessels

Chapter 1 The three plans of vessels

Chapter 2 Reductions of lines that one uses in the plans of vessels

Chapter 3 Machines to describe the preceding lines

Compared with *L'Art des armées navales*, this book appears quite hurried and unfinished, with uneven treatment among the sections. Only the parts of book 1 on fluid

resistance and ship stability appear to be well considered and reasonably complete in terms of providing novel concepts based on mathematically developed theories (which are discussed in chapters 3 and 4 of this book). The other parts are qualitative, in some places abruptly short—the chapter on the *dérive* consists of one sentence, unhelpfully stating that it simply reduces to the first chapter. Book 2 was really an outline of beam theory based on work done 60 years earlier by Galileo Galilei, which assumed that beams stayed rigid until rupturing under a certain load; Hoste showed no knowledge of more recent work done by Edmé Mariotte that analyzed beams as flexibly bending under loads.⁴ The third book provided a description of several novel machines, evidently of Hoste's design, to draw complex curves.

In this work, Hoste provided many mathematical suppositions and demonstrations on how to *think about* ship form, but gave no specific equations to actually *make* any calculations or estimates that constructors could use in a ship's design. Much of this weakness is due to the Aristotelian nature of his mathematics, which worked more by example than by rigorous analysis; in his analogies, for example, globes had the least resistance in fluids—supporting, in his view, the 1686 tests of a model with hemispherical bow and stern.

The “unfinished” appearance of this work is corroborated by the treatise Hoste apparently was writing at the time of his death in 1700, which was never published. “Architecture navale, ou Pratique de la construction des vaisseaux” (Naval Architecture, or the Practice of Construction of Vessels), which today exists only as a manuscript copy of the original, appears to have been intended to complement *Théorie de la construction des vaisseaux*. It, too, was divided into three sections: the first, a short recapitulation of his ship theories; the second, an examination of drawing techniques; and the third and largest, on how to build a ship.⁵ The work appears to have been almost entirely unknown, as it was never mentioned by later authors.

Théorie de la construction des vaisseaux should be seen not so much as a treatise on how to use ship theory in design, but as an explanation of how to think about ship design in a mathematical fashion. This method of treating ship theory by analogy rather than analysis became the norm for half a century, until Pierre Bouguer's *Traité du navire* completely changed the landscape.

Pierre Bouguer, *Traité du navire* (1746)

As detailed in the prologue, Bouguer wrote the first true synthesis of naval architecture, *Traité du navire, de sa construction, et de ses mouvements* (Treatise of the Ship, Its Construction, and Its Movements, figure 5.2) under extraordinary conditions during

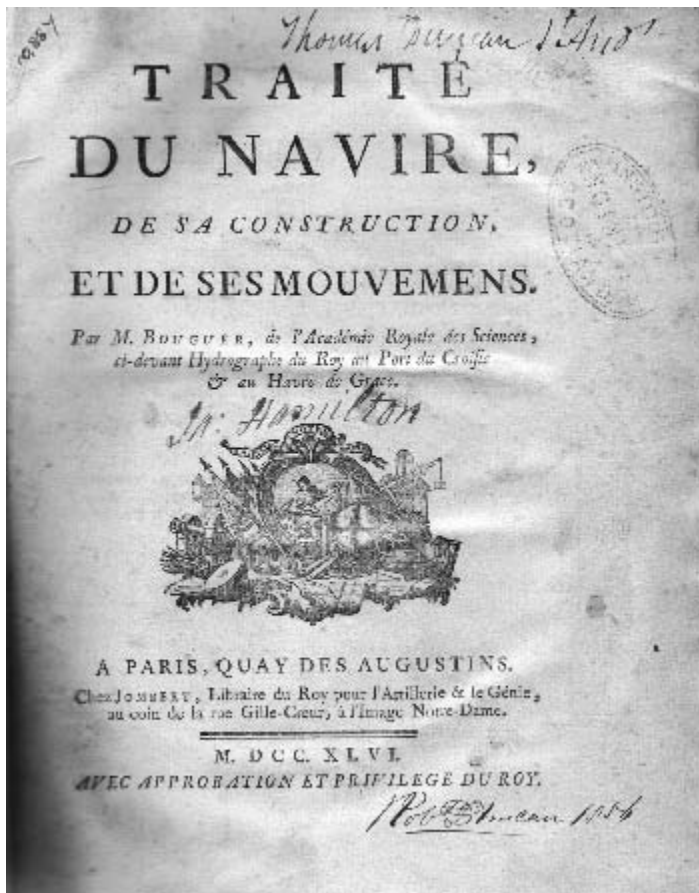


Figure 5.2

Pierre Bouguer, *Traité du navire* (1746).

the Geodesic Mission to Peru (1735–1744). On his return, he prepared the manuscript for review and approval by the Academy of Sciences, even as he was presenting to it his findings from the mission. On 12 May 1745 the mathematicians François Nicole and Alexis Claude Clairaut gave their endorsement for its printing, and three days later the secretary of the Academy, Grandjean de Fouchy, certified it for publication, meaning that the king (or, rather, Navy Minister Maurepas, to whom the book was dedicated) would foot the bill.⁶ The manuscript was sent to Charles-Antoine Jombert for typesetting and printing, with illustrations engraved by Pierre-Quentin Chedel and Charles-Nicholas Cochin. Bouguer, although living only a few blocks away, evidently did not closely follow the printing, as there were two full pages of errata in the back.

Just before the book was ready for publication, Bouguer hastily added a note responding to a critique of his masting theory made by Alexandre Savérien (as described in chapter 2).

In keeping with his original ideas expressed to Maurepas in 1734, Bouguer's text sought "not so much to trace the plans of vessels as to show how to choose between the methods of tracing plans and to reduce to a simple and easy calculation the advantage and disadvantage of each shape."⁷ It differed from previous and contemporary treatises by not providing specific proportions or how-to-build formulas, nor prescriptive treatments of subjects such as lading or admeasurement; rather, he used them as general background to his theoretical work.

It was a big book by the standards of the day, 904 pages and 12 fold-out plates. It sold for 15 *livres tournois* (about \$100 in 2002). The number of copies published was never recorded, but was probably less than 1,000, and it never achieved a second printing. It was certainly not a "best-seller"; Jombert continued to have unsold copies in stock until he went out of business in 1789.⁸ It was published in translation only in Italian, and no facsimile edition has yet been printed.

Traité du navire was divided as follows:

Book 1 General idea of construction

Section 1 Shape of the vessel and how to trace it

Section 2 Apparatus of the ship, including rudders, masts, cordages

Section 3 Strength of the ship, including its wood and ropes

Book 2 The vessel considered afloat, but not moving

Section 1 Weight of the vessel, its buoyancy and loading

Section 2 Distribution of the weight of the vessel, including a description of the metacenter

Section 3 Rolling and pitching of the vessel

Book 3 The vessel considered in movement

Section 1 Examination of the shock of fluids; the wind on the sails; water on the hull

Section 2 General solution to the principal problems of maneuvering

Section 3 Properties the vessel must have to steer well

Section 4 Qualities the vessel must have to carry sail well

Section 5 Properties the vessel must have to be fast and keep a straight course

This format has remained essentially unchanged for naval architecture textbooks for over 200 years; the latest edition of *Principles of Naval Architecture* also is divided into three books, each of which covers roughly the same topics.⁹

The first book contained a short guide to the types of ships and their parts, from the keel to the masts, followed by a review of the different methods proposed to draw the hull. Citing previous works by French and Spanish authors, Bouguer explained the reasons for choosing specific proportions and shapes, and the methods to create frame shapes derived from the midship (“master”) frame. He also devoted a number of pages to the mechanics of rowing, machinery (capstans, rudder), and masts and stays. The final section of the first book dealt with structures and strength, including a long and detailed examination of why ships hog (i.e., bend downward at the ends), and how to prevent it by using diagonal trusses. As part of this explanation, he provided the first calculation ever for the “bending moment” of a ship (i.e., the difference in force between weight and buoyancy that will cause a ship to bend), a calculation still used today in almost the same form.

In the second book, Bouguer examined displacement, admeasurement, and stability, introducing the concept of the metacenter for the first time. After recapitulating the buoyancy law of Archimedes, he provided several numerical methods to calculate the volume of the hull, focusing on the method of trapezoids. He then digressed into a long explanation of methods of admeasurement before providing the explanation and derivation of the metacenter, further developing it for various situations, and devoting several pages to the theory of roll and pitch. (This is discussed in chapter 4 of this book.)

In the third book, Bouguer first treated hydrodynamics, beginning with a general explanation of the shock theory of fluid resistance and the “impulsion” (force) of fluid on different shapes for the hull and sails. He offered the concept of “relative impulsion” between the bow and the midship section, which would later evolve into the “ratio of bow resistance” that became the crux of the hydrodynamic calculations used by French constructors. Bouguer then entered into a rather superficial discussion on maneuvering—he would treat it in more detail in later works—before reprising his concept of the *point vélique* from his 1727 treatise on masting. He ended with an examination of various bow shapes that would provide least resistance or greatest speed. (These subjects are treated in chapters 2 and 3 of this book.)

Bouguer, literally born to be a professor, had the rare gift of explaining concepts in a clear style that did not sacrifice precision, providing usable formulas with worked numerical examples (e.g., the rule of trapezoids for integrating areas and volumes) at every step of the way. In all his work (not just in naval architecture but also, for example, in photometry) he never used more mathematics than was absolutely necessary, preferring experimentation to pure theory, and geometry to analysis.¹⁰

For all that, the book initially fell upon a somewhat uncomprehending audience. In the review by the influential *Journal des sçavans* (Journal of Scholars), almost no attention was given to these theoretical insights; the focus was instead on how Bouguer defined hull lines, his methods of admeasurement, and his thoughts on lading—the same subjects covered in many prior shipbuilding treatises, from which this was a distinct break.¹¹ The reviewer excused Bouguer from using algebra that was “too sublime,” but hoped that he would provide the public with an abridged version of the work—all in all, rather like the apocryphal comment of Emperor Joseph II: “Too many notes, my dear Mozart, and too beautiful for our ears.”

Ultimately, *Traité du navire* was the principal catalyst for a new generation of scientifically trained constructors, who now had the tools to predict how their ships would float and sail—although this was also due to the textbook and school of Bouguer’s colleague Henri-Louis Duhamel du Monceau (as will be discussed later). In its era *Traité du navire* was seen as the “bible” of naval architecture; many of its theories were widely used for the better part of a century, and that of the metacenter is employed to this day.

Leonhard Euler, *Scientia navalis* (1749)

At the same time Bouguer was in Peru writing *Traité du navire*, Leonhard Euler was in Saint Petersburg, penning his *Scientia Navalis, seu Tractatus de Construendis ac Dirigendis Navibus* (Naval Science, or Treatise of the Construction and Operating of Ships, figure 5.3), the second great synthesis of naval architecture. Given the simultaneity of the two works, it appears that both Bouguer and Euler were inspired by the 1727 prize on masting (most probably by their common lack of understanding of hydrostatics) to continue their research into ship theory. Euler was further inspired by his 1735 critique of La Croix’s work on stability, so it was probably at his own suggestion that the Saint Petersburg Academy commissioned him to write a book on ship theory. He finished the first part of his work by 1738, and the second part was completed by 1741. However, it was not until after he left Russia to work at the Berlin Academy of Sciences that the Imperial Academy of Sciences of Saint Petersburg finally published it in 1749. It thus came to print a few years after Bouguer’s *Traité du navire*, and Euler gave credit to Bouguer’s work while carefully distancing himself from it, noting that he had no communication with Bouguer while he was in Peru. Euler dedicated *Scientia Navalis* to the president of the Academy, Kirill Grigorievich Razumovsky, then just 20 years old.

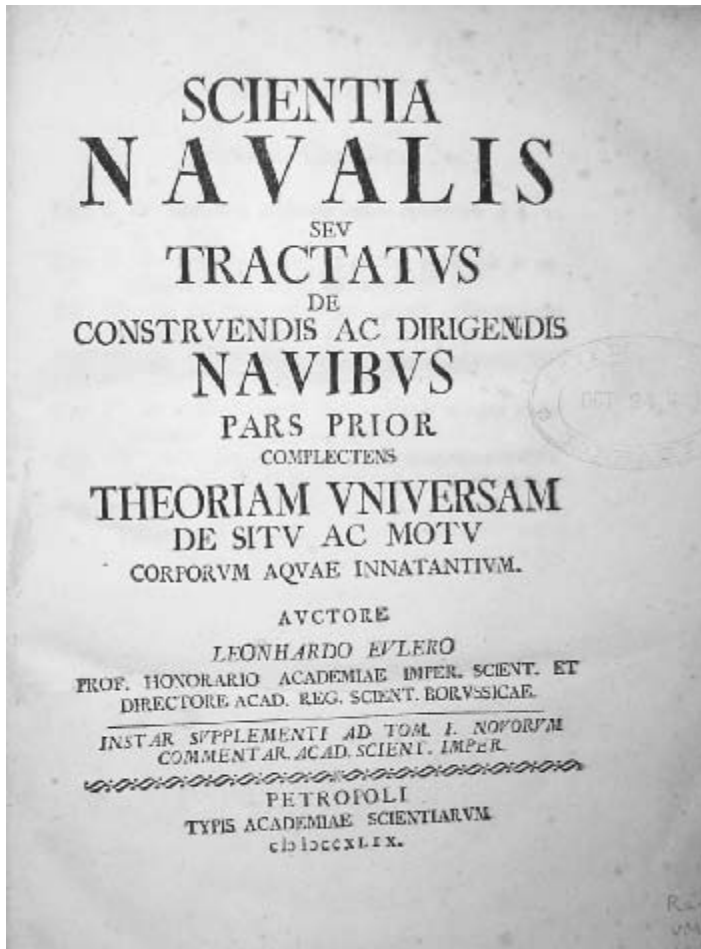


Figure 5.3

Leonhard Euler, *Scientia navalis* (1749). Credit: U.S. Navy Historical Center.

Euler divided his work into two separate books, a total of almost 1,000 pages, as follows:

Part 1 General theory of the location and motion of bodies floating on water

Chapter 1 The equilibrium of floating bodies

Chapter 2 The restitution of floating bodies to equilibrium

Chapter 3 The stability of floating bodies in equilibrium

Chapter 4 The effects of external forces upon floating bodies

Chapter 5 The resistance of water to moved plane figures

Chapter 6 The resistance of water to moved bodies

Chapter 7 The progressive motion of floating bodies

Part 2 Rules and precepts for constructing and steering ships

Chapter 1 Ships in general

Chapter 2 The equilibrium of ships

Chapter 3 The stability of equilibrium

Chapter 4 The oscillations of ships

Chapter 5 The inclination of a ship under the influence of arbitrary forces

Chapter 6 The effect of rudders

Chapter 7 The effect of oars

Chapter 8 The construction of rowed ships

Chapter 9 The force exerted by the wind on a sail

Chapter 10 The masting of sailing ships

Chapter 11 The ship on an oblique course

The first three chapters of part 1 were devoted to the mechanics of floating bodies and stability, followed by four chapters on fluid resistance (discussed in chapters 4 and 3, respectively, of this book). In hindsight these chapters provided not so much workable theories of ships as a series of statements of fundamental principles in hydrostatics and hydrodynamics—for example, the first mathematical elucidation of Archimedes' principle and the establishment of x - y - z axes of inertia. In the first five chapters of part 2, Euler interpreted the results of the stability theory he developed in part 1, including oscillations of ships and the combined heel and trim under oblique sail forces. He then provided mechanical analyses of forces on rudders, oars, and sail before proceeding to discuss Bouguer's *point vélique* and the *dérive*.¹²

A landlubber all his life, Euler never discussed in *Scientia Navalis* the practical aspects of shipbuilding or design. Even so, it was an ambitious work. Although Euler tackled

essentially the same problems as Bouguer, he did so with much greater mathematical rigor, and presented the solutions as global equations applicable to any floating body—for example, he did not automatically assume that floating bodies would be symmetrical, the simplifying assumption Bouguer applied to ships. Each was aiming at a different audience. Euler was creating fundamental hydrostatic and hydrodynamic theory, in Latin, for his fellow mathematicians; *Scientia Navalis* was laid out (like Hoste's work) as a mathematical textbook, with each chapter containing propositions, theorems, solutions, corollaries, and scholia. Bouguer, supported by the French navy, was mixing theory and practical shipbuilding, in seaman's French, to provide constructors with a guide for designing ships. As the historian of fluid mechanics Julián Simón Calero states, "The ships [of Euler] were defined by equations; those [of Bouguer] had frames and ribs."¹³

Euler was later convinced, principally by the British naval officer Charles Knowles, who was working in the Russian navy at the time, to write a more accessible edition of the book, aimed squarely at naval constructors, that stripped away most of the theory and kept the practical results.¹⁴ This appeared in 1773 as an abridged version in French, *Théorie complotte [sic] de la construction et de la manœuvre des vaisseaux* (Complete Theory of the Construction and Handling of Vessels). It eliminated several subjects covered extensively in *Scientia*—for example, the long and complex calculations of fluid shock—and instead provided simplified calculations for the popular "ratio of bow resistance." This book was subsequently translated into Russian, English, and Italian, and the various editions brought a fair sum of money to the Saint Petersburg Academy and to Euler. In 1776, at the command of the French minister of the navy, Anne-Robert-Jacques Turgot, it was reedited by a French publisher to correct the grammar, and issued as *Théorie complète de la construction et de la manœuvre des vaisseaux*, to be used by French naval constructors and students. This was done without Euler's consent, although he was later paid handsomely for it.¹⁵

Henri-Louis Duhamel du Monceau, *Éléments de l'architecture navale* (1752)

The publications of *Traité du navire* and *Scientia Navalis* coincided with the early days of what would become the École des Ingénieurs-Constructeurs de la Marine (School of Engineer-Constructors of the Navy), established in 1741 by Minister of the Navy Maurepas to educate future constructors in the scientific and practical elements of ship design and construction. Maurepas chose the botanist Henri Louis Duhamel du Monceau (already inspector general of the navy) as the head of the "Little Navy School," as it was then called. One of Duhamel du Monceau's tasks was to develop

the curriculum for the students, and to this end he set about writing a textbook, published as *Éléments de l'architecture navale, ou Traité pratique de la construction des vaisseaux* (Elements of Naval Architecture, or Practical Treatise of the Construction of Vessels, figure 5.4) in 1752. It was, in fact, a mixture of practical design and construction techniques with ship theory, as shown by the table of contents:

- Chapter 1 Of the types and dimensions of the principal pieces which enter in the construction of vessels
- Chapter 2 Of the general proportions for the construction of vessels
- Chapter 3 Method for tracing the profile of a 70-gun vessel
- Chapter 4 Method for tracing the body plan of a 70-gun vessel
- Chapter 5 Of horizontal plans and occasionally the waterlines and frames represented on the elevation and body plan
- Chapter 6 Another method for making the body plan and profile of a vessel
- Chapter 7 General remarks on construction
- Chapter 8 Method for knowing, on the plan of a vessel, what is the height of the battery
- Chapter 9 Method for calculating the water resistance of the bows of vessels
- Chapter 10 Method for knowing on the plan if the vessel one projects, carries sail

Most of the book was devoted to the drawing principles, generalized but still highly geometric, to be used during the design of the vessel, with numerous figures to illustrate the processes. Only the last three chapters (130 out of 480 pages) concerned ship theory per se, and very selectively at that: calculation of displacement by using the method of trapezoids; ratio of bow resistance; and centers of gravity and stability. Duhamel had been in close communication with Bouguer during the writing of his book,¹⁶ and he based the theoretical elements directly on *Traité du navire*, frequently referring the reader to it for further explanation. Although Duhamel undoubtedly knew of Euler's *Scientia Navalis*, the fact that it was both highly mathematical and in Latin made it comparatively inaccessible as a student's sourcebook.

Duhamel du Monceau's great achievement in *Éléments* was to render the complex mathematics of Bouguer into a systematic format that students could use by rote. Duhamel well understood the need for such simplification, having been a mediocre student with a fear of mathematics.¹⁷ For example, Duhamel's synopsis of the "shock of fluids" theory was completely devoid of equations, explaining the concept in general terms instead, complete with sets of tables that codified the hydrodynamic calculations.

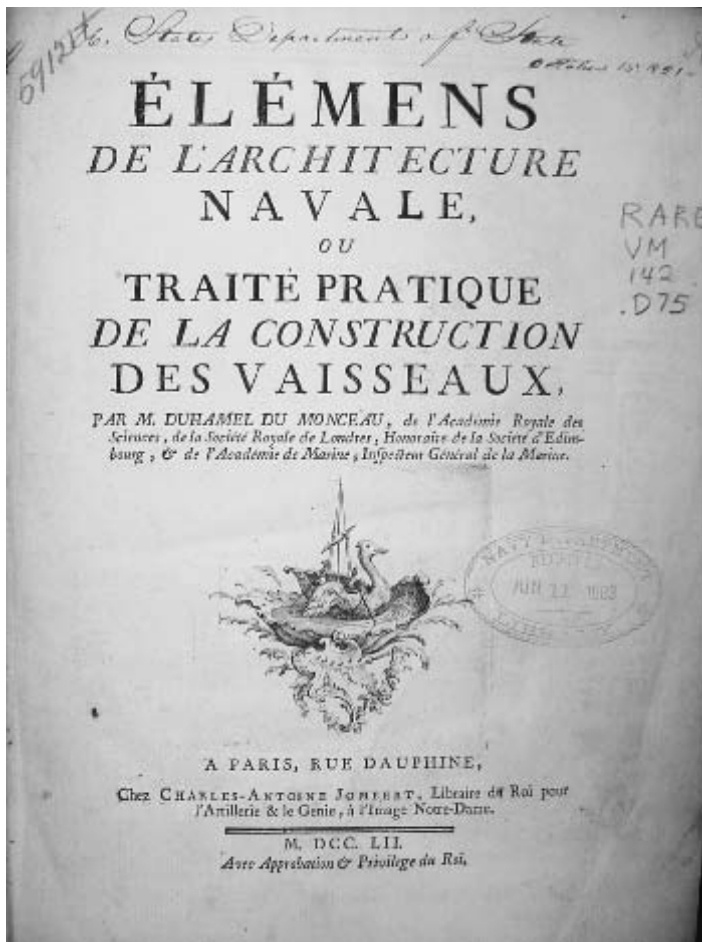


Figure 5.4

Henri-Louis Duhamel du Monceau, *Éléments de l'architecture navale* (1752). Credit: U.S. Navy Historical Center.

It is interesting to compare *Éléments* with another work written at exactly the same time but never published. “*Répertoire de construction*” (Repertoire of Construction) was written in 1752 by the Rochefort chief constructor, Pierre Morineau, “for the instruction of his children.”¹⁸ In over 400 pages of compact handwriting, Morineau described in great detail, and for every type of ship in the French navy, the precise proportions of the various parts of the ship, the dimensions and weights of every piece (wood or metal); the lines of the vessels in tables of offsets and line drawings; and the amount of stores each vessel carried. It was a highly practical but also highly prescriptive work that described exactly how Morineau built his ships; more to the point, it was devoid of any explanation of why he chose those dimensions or proportions, and it did not provide more general rules and methods for evolving a ship in a different manner. The fact that it was never published indicates that this dogmatic approach to ship construction was out of favor by the 1750s. By contrast, *Éléments* was more generalized in its explanations, and was seen to meet the growing interest by administrators and constructors alike in developing a mathematical and scientific basis for ship design and construction.

It certainly arrived at the right time, for *Éléments* quickly became a best-seller, and was republished in 1758 (a facsimile appeared in 1994). Although many constructors around Europe in the mid-1700s could read French and knew of *Éléments*, its popularity was such that it was translated into Dutch, German, and English, and later into Danish, within a decade of its publication.¹⁹ For many navies, *Éléments* became the de facto textbook of naval construction well into the next century.

Jorge Juan y Santacilia, *Examen marítimo* (1771)

Some ambiguity surrounds the origins of *Examen marítimo, teórico práctico, o Tratado de mecánica aplicado á la construcción, conocimiento y manejo de los navios y demás embarcaciones* (Maritime Examination, Theoretical and Practical, or Treatise of Mechanics Applied to the Construction, Design and Handling of Ships and Boats, figure 5.5). Jorge Juan y Santacilia had returned from the Geodesic Mission to Peru in 1746, the year Bouguer’s *Traité du navire* was published. In 1749, the year Euler’s *Scientia Navalis* went to press, he was sent by Spain’s first minister, Zenón de Somodevilla y Bengoechea, marquis of Ensenada, on an espionage mission to Britain to bring back naval secrets (described in chapter 6). On 5 February 1750, while in London, Juan y Santacilia wrote to Ensenada, requesting permission to continue writing a treatise on the fabrication of ships that he had already begun, arguing that shipbuilding was left in the hands of “mere practitioners” who were “without the



Figure 5.5

Jorge Juan y Santacilia, *Examen marítimo* (1771). Credit: Escuela Técnico Superior de Ingenieros Navales, Madrid.

slightest book, treating with some rationality," the basic laws of mechanics and geometry that governed ship design. Juan y Santacilia had almost certainly known that Bouguer was writing *Traité du navire* during the Geodesic Mission, and was undoubtedly aware of its publication in 1746. As well read as he was, he also likely knew of *Scientia Navalis*. Given that he already had the strong support of Ensenada, it is not clear why he needed to misrepresent the state of knowledge at the time.

Juan y Santacilia need not have worried. On 5 March 1750 Ensenada enthusiastically replied that the king wanted him not only to write this book but also to include plans of ships and their properties.²⁰ A month later, Juan y Santacilia returned to Spain, where he began work in earnest on the treatise, most likely finishing the majority of the work in the early 1750s.²¹ Unfortunately, Ensenada fell from power in 1754, so Juan y Santacilia was left without political backing. Publication of the book lagged until 1771, when it was finally printed by the Madrid publisher Francisco Manuel de Mena.²²

Examen marítimo consisted of two almost independent volumes. It began with a 53-page prologue mostly devoted to a history of naval architecture and a rationale for this publication, in which Juan y Santacilia echoed his letter to Ensenada by insisting that construction of vessels was left to "mere carpenters." Volume 1, at almost 400 pages, was essentially a comprehensive mathematical treatise on solid mechanics and fluid mechanics, with an appendix on kites. The format of this first volume was very much like Euler's *Scientia Navalis*, with propositions, corollaries, and scolia, which were cited during the explanations of ship theory found in the second volume.²³

Volume 2, the synthesis of naval architecture which concerns us here, followed more closely the structure of Bouguer's *Traité du navire*, although it is much more finely subdivided (here I give only the basic headings and description of contents):

Book 1 On the construction of the ship

Types, properties, plans, geometry

Book 2 Examination of the body of the ship; its centers, forces, resistance, and moments

Displacement and centers of gravity; horizontal resistance; sail forces and moments; hull strength

Book 3 Of the machines that move and steer the ship: sails; rudder; oars

Book 4 The actions and movements of the ship

Bow resistance; ship speed in relation to wind speed; *dérive*; form of sails; heeling of the ship from the wind; steering the ship; roll and pitch

Book 5 On the maxims and rules that result from the preceding

Strength of the ship; size of ships; course and direction; steering; roll and pitch

Although Juan y Santacilia built extensively upon the work of Bouguer, Euler, and others (there are 267 citations in his book), he carefully chose which theories to adopt, expand upon, or dismiss. For example, in his calculations of the *dérive* in book 2, he did not assume (as did Bouguer and Euler) that the ship was a simple geometric body, but went beyond them by calculating the *dérive* of each section of the ship according to its shape and angle of attack with the water, then integrating the sections to develop the overall *dérive*. Neither did he adopt or even mention Bouguer's *point vélique*, which even Euler had done. However, he relied heavily on both Bouguer and Euler in book 4 when introducing his theories of roll and pitch, essentially adding terms to their theories that accounted for the action of sails. In book 5, he applied the results of the previous four books to create a series of rules and observations for practical ship construction—for example, accounting for roll and pitch forces to size the thickness of the frames, and noting that due to lower bending moments, the planking at the bow did not have to be as thick as amidships.²⁴ Although Juan y Santacilia rejected much of ship theory for practical use (as described previously), he nevertheless used this theoretical understanding to inform his choices for hull form, material, and sail plans during his tenure as chief constructor. For example, he redistributed the thickness of frames and planks according to his insights above, so as to give a lighter yet stronger hull.

Jorge Juan y Santacilia died from a cerebral amebic infection in 1773, two years after *Examen marítimo* was published.²⁵ He did not live to see its enormous success—it was widely cited, translated, and even reedited for over 50 years. It was first translated into French in 1783 by the hydrographer Pierre Lévêque as *Examen maritime, théorique et pratique*, a very influential textbook that was used for the School of Student Engineer-Constructors of the Navy. It also formed the basis for many of the entries in the colossal *Encyclopédie méthodique: Marine* in the 1780s. A “corrected” volume 1 was republished in 1793 by the Spanish naval officer Gabriel Ciscar y Ciscar (a successor in several of the posts held by Juan y Santacilia). In 1818 Lévêque’s translation was retranslated into Italian, and as late as 1824, the French naval officer Abraham-Christophe-Pierre, marquis of Poterat, revised and corrected it as *Théorie du navire* (Ship Theory).²⁶ Facsimile editions of the original were published in 1968 and 1992.

Fredrik Henrik af Chapman, *Tractat om skepps-byggeriet* (1775)

Of all the great works in this chapter, Chapman’s *Tractat om skepps-byggeriet, tillika med förklaring och bevis öfver Architectura Navalis Mercatoria &c.* (Treatise on Shipbuilding, with Explanations and Demonstrations Respecting the *Architectura Navalis Mercatoria*, etc., figure 5.6) was the least innovative in its approach and contained few new



Figure 5.6

Fredrik Henrik af Chapman, *Tractat om skepps-byggeriet* (1775). Credit: U.S. Navy Historical Center.

theoretical concepts. It apparently was written more as a textbook than as an original work of ship theory, but its unsystematic construction was more akin to a set of memoirs, especially compared with Duhamel du Monceau's carefully laid out *Éléments de l'architecture navale*. Being in Swedish, it was of limited utility around Europe. Yet of all these great works, it has become by far the best known, appearing in more book lists and bibliographies than any of the others. It was widely translated and republished over the years, initially in a 1779 French translation (*Traité de la construction des vaisseaux*), followed in 1781 by a superior and more widely known one by Vial du Clairbois for use in the School of Student Engineer-Constructors of the Navy. This gave

the work immediate, widespread attention, and it was often cited in secondary works. In 1820 the British mathematician James Inman published an English translation (*A Treatise on Ship-building*) for use in the first School of Naval Architecture, further increasing its fame. In recent years the work has been reprinted in popular editions and commented on in several languages.²⁷

As the title suggests, it was a companion piece to Chapman's 1768 *Architectura Navalis Mercatoria* (Merchant Naval Architecture), a collection of highly detailed drawings of both merchant and naval vessels that showed, among other things, the ships' displacement and metacenter. Although Chapman had promised its companion to explain the calculations and measurements by 1769, he did not complete *Tractat* until 1775. But the resulting work was more than a mere set of calculations; it was in fact a compilation of his knowledge of naval architecture to that point.

Tractat was haphazardly laid out in 12 chapters:

- Chapter 1 On the displacement of the ship and the center of gravity of the displacement
- Chapter 2 On the stability, or resistance to heeling
- Chapter 3 On the center of gravity of the ship considered as a heterogeneous body
- Chapter 4 On the resistance which a ship in motion meets with from the water
- Chapter 5 On the center of effort of the wind on the sails, and the sails' moment around the ship's center of gravity
- Chapter 6 On the dimensions and different forms of ships
- Chapter 7 On the proportions of privateers
- Chapter 8 Proportions of masts and yards for merchant ships
- Chapter 9 On different matters relating to the practical part of construction
- Chapter 10 On the property in ships of being ardent [to head into the wind]
- Chapter 11 On the measurement for tonnage and stowage
- Chapter 12 Description of the drawings in *Architectura Navalis Mercatoria*

The first three chapters consisted primarily of simplified descriptions of Bouguer's stability theories, with the important addition of Simpson's rule to calculate displacement. In chapters 4 and 5, Chapman explained the concepts of the solid of least resistance, the ratio of bow resistance, and the *point vélique*; in addition he gave the results of his experiments on model resistance that he had conducted in the 1770s. The last half of the book was more practical in nature; Chapman applied various rules of algebra and geometry to determining the sizes and shapes of the hull, fittings, masts,

and sails, most famously introducing his “parabola method” to construct hull lines (described previously in this book).

Why did this book become so famous? Part of the explanation must be aesthetic; Chapman was a fine draftsman, taking great care to make *Tractat* and its earlier companion, *Architectura Navalis Mercatoria*, beautiful to look at, thereby elevating mere construction and scientific drawings to works of art. It may also be that Chapman examined the construction of merchant ships, whereas most other authors were concerned with naval vessels. Another explanation, supported by the fact that the translations were intended for schools of naval architecture, is that he laid out easy-to-follow (though hardly systematic) rules for construction, expressed in straightforward mathematics—the up-and-coming language of engineers and constructors—that was understandable by students.²⁸ For example, Chapman’s “parabola method” of construction, though having no basis in hydrodynamic theory, may have appealed to constructors who had not mastered the subtleties of calculus yet wanted to appear to be scientific in their approach. For whatever reason, *Tractat om skepps-byggeriet* was seen as filling a need in the increasing professionalization of constructors, which is the subject of the next and final chapter in this work.

6 Genius and Engineering

The French word *génie* means both “genius” and “engineering.” The Latin word *ingenium*, meaning both “engine” and “engineer,” comes from the Latin root *geno*, meaning “to create”; both intelligence and inventiveness (ingenuity) were considered the defining characteristics of the engineer.¹ Until the mid-1600s an “engineer” generally worked on fortifications, roads, and other civil works, and was seen as occupying a high social position. Constructors were the “mere carpenters” who built ships. This chapter explores the process of professionalization of naval constructors, beginning with France, Spain, and Denmark and spreading to other nations, where governments were enacting greater control and oversight of the design and construction of ships, requiring systematic education and formation coupled with an increasing use of theoretical calculations. As a result of this process, naval constructors began to be seen less as “mere carpenters” and more as part of the engineering profession, giving them a higher social standing. The end of this chapter provides the general conclusion to this work, describing the leap of naval architecture from the burned-out Scientific Revolution into the Industrial Age.

France’s Corps of Engineer-Constructors of the Navy

Beginnings: The Corps of Military and Civil Engineers

The first professional corps of engineers was instated in France in 1676, by Sébastien Le Prestre, lord (later marquis) of Vauban, as part of a general system of military professionalization begun by Colbert. Before then, French officers specializing in artillery and fortifications were mixed in with the infantry. Vauban selected the brightest officers to serve in his Corps des Ingénieurs de Génie Militaire (Corps of Engineers of Military Engineering), and though they did not yet have a dedicated school, they learned both the theory and the practice of engineering in the field. Under Vauban they built the extensive system of forts across France that gave the Corps its worldwide renown.

In 1716 the Corps des Ingénieurs des Ponts et Chaussées (Corps of Engineers of Bridges and Roadways), the civilian equivalent of Vauban's corps, was created to supervise the construction of public roadways, bridges, canals, and harbors.²

The two French engineering corps did not establish their own formal educational system for over half a century. The École Nationale des Ponts et Chaussées (National School of Bridges and Roadways), which exists today, was established at Paris in 1747, and gave very practical instruction in design, materials, and other relevant subjects. A year later, the École Royale du Génie (Royal School of Engineering) was established at Mézières in the Ardennes, in the north of France. Compared with the civilian school, the curriculum at Mézières was highly theoretical, with mathematics professors and examiners including Charles Étienne Louis Camus, Étienne Bézout, and Charles Bossut leading the field. Though it was ostensibly an army school, several notable figures in ship theory, such as Jean-Charles de Borda and Pierre-Louis-George du Buat were educated there.³

Both schools depended on a series of texts that gradually incorporated theory and practice in civil and hydraulic engineering, the most important of which were by Bernard Forest de Bélidor, an engineer and first director of the Royal School of Artillery (established in 1720). His first books on fortifications and artillery in the 1720s were generally practical, incorporating some mathematics to establish, for example, the ballistics of cannon shot and the breaking force of beams. By the late 1730s, Bélidor was incorporating theories of rational mechanics into the design and construction of civilian structures. His monumental *Architecture hydraulique* (Hydraulic Architecture), printed in four massive volumes between 1737 and 1753, was the first to apply differential and integral calculus to civil engineering problems of canal flow, pipe pressures, and hydraulic loads on locks and weirs. It was the civil engineering analogue to Bouguer's *Traité du navire*, a synthesis of the subject that applied mathematical principles to practical design and construction.⁴

French Maritime Education and Formation Before the Corps of Constructors

In contrast to the professionalization of military engineers, the process for French naval constructors was roundabout and did not even include them at the beginning. The first comprehensive instruction in ship theory, design, and construction in France was given not to the constructors but to naval officers and cadets, as part of Colbert's attempts to professionalize the entire navy. In 1669 he had created a small naval college at Saint Malo, in 1679 an artillery school, and by 1681 a series of hydrography schools, run by Jesuit scientists, to train pilots. The curriculum for the latter was based on George Fournier's *Hydrographie* (Hydrography), of which the first volume

was titled *Naval Architecture*. Both merchant and naval officers were taught the basic proportions of ships, how to trace hull lines, selection and felling of trees, and methods of construction and outfit.⁵ Pierre Bouguer, as a professor of hydrography, naturally saw the furtherance of naval architecture as an integral part of his position.

Colbert created the Gardes de la Marine (Navy Guards) in 1683 as a formal route for cadets to become naval officers, similar to the existing army cadet system. The curriculum, put into place at the main dockyards of Rochefort, Brest, and Toulon, incorporated practical training in gunnery and fencing with theoretical instruction in mathematics, fortifications, hydrography, and naval construction.⁶ The Navy Guards would graduate to form the nucleus of the naval military corps, the *Officiers de l'Épée* (Officers of the Sword). Colbert also instated a second cadre of naval officers, *Officiers de la Plume* (Officers of the Pen), occupied with naval administration of matériel, victualing, pay, and other duties (this group included intendants and commissioners). Officers of the Pen were recruited from both the civilian sector and former Sword officers, though there was no substantive distinction between civilian and military ranks in that era. Officers of the Pen exercised power in all naval matters except strictly military ones, including supervision of dockyards and naval constructors (who were civilians outside the officer ranks). However, Officers of the Sword also actively participated in dockyard activities, such as receipt and inspection of raw material including masts, manufacture of ordnance, and ship construction.⁷

Colbert saw that naval officers should have a good understanding of ship design theory and practice, given that they advised his administration on ship construction, both as part of biweekly construction councils that he had established in 1671, and in their after-campaign reports that critiqued a ship's performance. In 1680 he instructed his intendants at the Rochefort, Brest, and Toulon dockyards to establish formal schools of naval construction (Marseilles was soon included). Senior constructors—or, more often, their sons—were to teach Navy Guards and Officers of the Sword their methods of graphical design, selection of dimensions, and construction and outfit of ships from galleys to first-rates.⁸ Constructors, however, were understandably reluctant to reveal their trade secrets, and often refused to give proper instruction. Pierre Chabert at Marseilles first complained that his throat could not handle speaking loudly five times a week, and capitulated only under threat of imprisonment; his resulting lectures were intentionally dense and incomprehensible.⁹ In the event, these formal schools seem to have disappeared within a few years, the teaching of naval construction, often by Jesuit professors of mathematics and hydrography such as Paul Hoste, being folded into the general curriculum of the Navy Guards.¹⁰

Duhamel du Monceau's "Little Navy School"

Formal education of French naval constructors was much longer in coming, in part because they had greater hurdles to overcome than did naval officers. Each dockyard was its own world, and the education and training of its constructors (often fathers and sons) generally took place within its own walls, though more capable sons would circulate between dockyards to broaden their knowledge.¹¹ The education in French dockyard schools, as in the rest of Europe, was not formalized and almost entirely practical—how to fell trees, season wood, lay off frames. Basic arithmetic and geometry were essential for this, but literacy was not, and many constructors were illiterate. However, this educational system evolved in the mid-1600s, in part due to the rise of Jesuit and other colleges in and around cities, including the major dockyard cities, which catered to the growing middle class of professionals eager to put their children on the road to social advancement.¹² Constructors began sending their sons to primary schools and colleges, where they learned to read, write, and use basic geometry; but this was still in preparation for their practical training in the dockyards. This changeover from illiteracy to literacy seems to have been accomplished within a single generation, and is graphically demonstrated in figure 6.1, a detail from the estimate (*devis*) for the 58-gun *Courageux* (1677). The document shows the signatures or marks



Figure 6.1

Detail of *devis* of *Courageux* (1677), showing the mark of Honoré Mallet (H.M.) and the signature of his son Pierre Mallet. (Service Historique de la Défense, Département Marine, Rochefort, côte 1L3 /18, folio16). Credit: Service Historique de la Défense, Département Marine.

of the members of the construction council who approved it. Honoré Mallet, the chief constructor, who could neither read nor write, put his mark “H.M.” in the middle of the other signatures; his literate son Pierre signed his full name just below.¹³

The impetus for a formal education for naval constructors came from Henri Louis Duhamel du Monceau (figure 6.2), with the support of Minister of the Navy Maurepas. The very strong and long-lived relationship between the two men had begun in 1731, when Maurepas requested the Academy of Sciences to research and recommend a uniform practice for preserving wood destined for the construction of ships.¹⁴ Maurepas was impressed with the response of Duhamel du Monceau, an up-and-coming botanist, so he continued to task him with unofficial assignments for the navy.



Figure 6.2

Henri-Louis Duhamel du Monceau. Oil by François-Hubert Drouais. Credit: Musée Nationale de la Marine, Paris.

Maurepas kept Duhamel du Monceau on the go, sending him around France to solve various problems for the navy, and even on an espionage mission to Britain to examine some developments in gunpowder satchels. In 1737 Maurepas asked him and another botanist, Georges-Louis Leclerc, count of Buffon, to examine the strength of wood for naval use, with Buffon as a sort of junior partner.¹⁵ It therefore came as a blow when in 1739 Maurepas named Buffon, not Duhamel, as intendant of the royal garden. However, the blow was softened when later that year Maurepas elevated Duhamel to inspector general of the navy, a position of enormous responsibility that had not existed since the time of Seignelay; Duhamel held the position until his death from a stroke in 1782.¹⁶ The fact that Maurepas had selected a scientist and not a constructor underlined his confidence in the scientific establishment and his lack of confidence in his naval establishment (by contrast, all of the British navy's chief surveyors were constructors).

In 1740, Duhamel du Monceau met 18-year-old François Guillaume Clairin-Deslauriers, an apprentice student constructor at Rochefort; impressed with his abilities, he petitioned Secretary of the Navy Maurepas to send him to Paris for further education. Duhamel du Monceau tutored Clairin-Deslauriers at his parents' home at 13 quai d'Anjou on the north side of Île Saint-Louis in Paris.¹⁷ In 1741 he made a further petition to Maurepas, requesting that a "petit école de marine" (Little Navy School) be established in Paris for the formal education of selected student constructors from the various dockyards, with a stipend paid to the students for their living expenses. The Little Navy School (small in terms of number of students) continued to be conducted in Duhamel's parents' house, and it appears that Duhamel bore the brunt of the costs for instruction materials, including an expanding collection of ship models. He obtained the services of the mathematics professor Charles Camus, and called upon the constructor Blaise Ollivier to provide practical instruction, which he did until his death in 1746.¹⁸

It is not clear what source material was used apart from basic texts of geometry and calculus, though it undoubtedly included works by Paul Hoste, Johann Bernoulli, and Henri de Pitot, as well as the various Academy prizes on naval subjects. In 1744 Bouguer had returned from Peru with his manuscript of *Traité du navire*, which Duhamel du Monceau immediately sought to use as a principal text for his school, and did so following its publication in 1746; Bouguer later taught at the school along with Camus. Instruction was probably sporadic, given Duhamel du Monceau's grueling travel schedule and obligations of the other instructors. For the first year, Clairin-Deslauriers was the only student. Slowly the students trickled in, to the point that the house was bursting with a dozen bodies and many more ship models.¹⁹

In 1748 Duhamel du Monceau again petitioned Maurepas, this time to move the Little Navy School to the royal library on rue Richelieu (the current site of the National Library of France). It was placed in the basement, along with the collection of ship models that Duhamel du Monceau had just donated to the king (it formed the nucleus of the present collection at the Musée de la Marine [Navy Museum]).²⁰ However, the models were exposed to damaging humidity, so in 1753 Duhamel du Monceau petitioned the successor to Maurepas, Navy Minister Antoine-Louis de Rouillé, count of Jouy, to move the school and the models to the Louvre Palace. The ship models were placed in a magnificent, light-filled, high-ceilinged room with a mezzanine that is now part of the Hall of Bronzes, room 32 of the Sully Wing (figure 6.3). The Little Navy School, also known as the *École du Louvre* or *École de Paris* (School of the

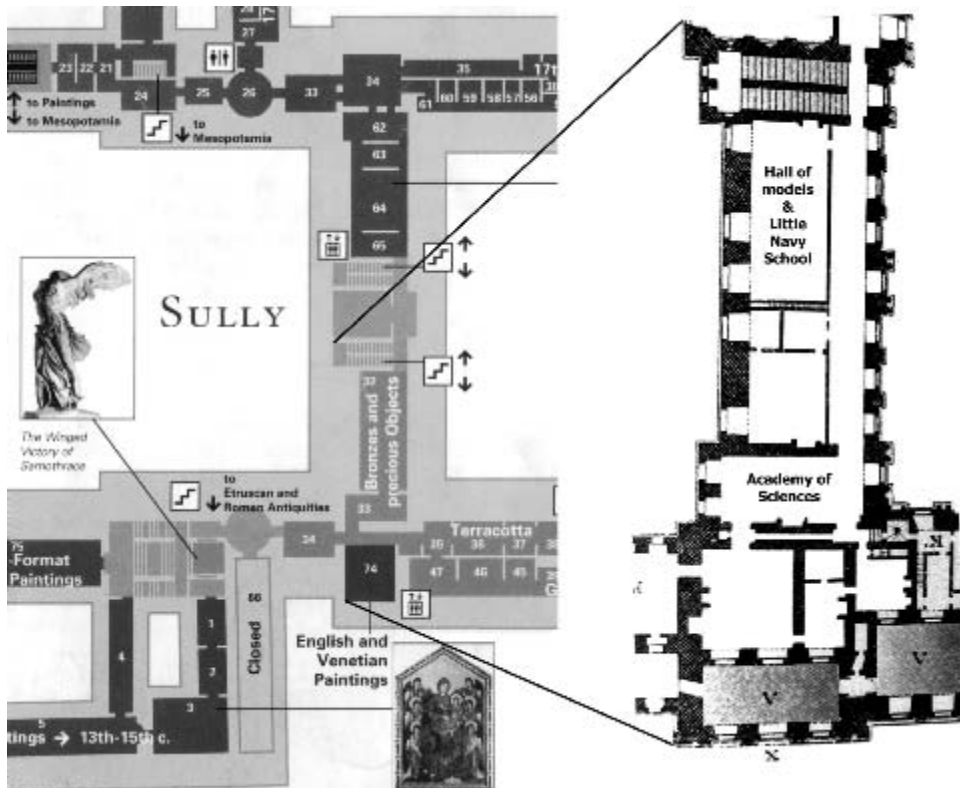


Figure 6.3

Little Navy School and Academy of Sciences in the Louvre. Left: Current plan. Right: Louvre in 1756. (Blondel, *Architecture française* [1756]). Credit: Musée du Louvre, Paris.

Louvre/Paris)—there apparently was not an official name—was almost certainly in that room, with students instructed among the models, although no historical records specifically mention the school's location within the palace. This move from the royal library to the Louvre was more than a way to get more light and less humidity; it put the Little Navy School next to the seat of scientific political power. As shown in the figure, the school was next to the meeting rooms of the Academy of Sciences, giving the scientists a continual exposure to maritime activities.²¹ This may help explain why academicians were so interested in naval and maritime matters for their studies, choosing fluid mechanics, naval architecture, and navigation as the subject of over a quarter of the Rouillé Prizes. At the same time, this proximity to the Academy afforded the naval students twice-weekly contact with leading scientists and visiting dignitaries.

In 1752 Duhamel du Monceau's *Éléments de l'architecture navale* (Elements of Naval Architecture), described in chapter 5, became the principal textbook for the school, along with texts by Bouguer and others. Instruction remained a hit-and-miss affair, and the comings and goings of students from dockyard to school was sporadic, as the course was not required of all constructors. Nevertheless, there were typically 10 to 12 students at any given time. The Seven Years War (1756–1763) set in motion a series of cutbacks that included the 1759 closure of the School of the Louvre by Minister of the Navy Nicolas-René Berryer, on the grounds that the students were needed for war efforts at the dockyards.²²

The 1765 Ordinance and the Standardization of the French Navy

That closure was temporary, for soon after the war ended in 1763, the next minister of the navy, Etienne-François, duke of Choiseul, planned a sweeping overhaul of the service, the largest since Colbert's 1689 ordinance. Choiseul's ordinance of 25 March 1765 set out new regulations concerning every aspect of the navy: functions and duties of the officers, sailors, and naval infantry; naval hospitals and doctors, and pensions for the wounded; dimensions, armament, and outfit of ships; and the creation of the Navy Council and the War Council.²³ The aim of this ordinance was to create a new system of professionalization and standardization of the entire service that would be tightly controlled by the central ministry, and not left to the devices of the constructors and administrators in the various ports and dockyards. In short, the 1765 ordinance was the first realization of Colbert's original goal of a complete standardization of his navy.

Choiseul, under Duhamel du Monceau's influence, included in the standardization of naval ships a complete list of the information to be on the plans and estimates, such as the metacenter and the ratio of bow resistance. These calculations gave naval

administrators a measure of control over, and confidence in, both the constructors and the ships they built. For these administrators, learned in the classics, it was more comprehensible to discuss ship design in mathematical and mechanical terms rather than in the arcane language used in the dockyards. The fact that constructors were required to perform these calculations meant that they had a firm grasp of the fundamentals of ship theory, and by ensuring that these calculations were carried out and reviewed by senior constructors, the chances of a major problem were, in the administrators' view, diminished.

To guarantee that constructors had this fundamental knowledge of ship theory and practice, the ordinance established the regulations, military rank, pay structure, and functions of an entirely new body, the *Ingénieurs-Constructeurs de la Marine* (Engineer-Constructors of the Navy), specifically charged with the construction and repair of all navy ships. These men would be educated in a standardized manner, using textbooks for instruction rather than the older, more haphazard master-apprentice system.²⁴ Furthermore, their work would be overseen by a single individual to ensure uniformity of design.

In the event, the 1765 ordinance was a vital prelude to the more complete standardization of ship designs ordered by Minister of the Navy Charles-Eugène de la Croix de Castries in the early 1780s. After a series of problems with the fleet, Castries appointed Jean-Charles de Borda, a mathematician with no design experience, to develop a standardized set of designs. Castries did this on the recommendation of the influential vice admiral Aymar-Joseph, count of Roquefeuil-Kerlouet, who had supported Borda's experiments on fluid resistance in the 1760s. In Roquefeuil's eyes, Borda was the most qualified person to "enlight[en] and perfect" the constructors because he was one of the most distinguished mathematicians of the day.²⁵ Borda worked with the young constructor Jacques-Noël Sané to create standard designs for the 74-, 80-, and 118-gun ships that became the backbone of the French fleet until the 1830s. Although these standard designs owed little to theoretical developments, their execution could not have been accomplished with any confidence, in the view of the administrators, without the scientifically trained corps of naval constructors that had been formed to oversee this development and to ensure the technical adequacy through the use of mathematics and theory.

The Evolution of France's Corps of Constructors

This rise of shipbuilders from "carpenters" to "constructors" was a long time in coming. Although titles alone did not confer new knowledge, they did mark an elevation in social rank that, in effect, allowed them to move within increasingly wider

professional circles. In the late 1600s, the title *charpentier* (carpenter) denoted a craft activity, and indeed most shipbuilders spent their lives in and around the dockyards, having little interaction with the naval officers and administrators who controlled the functions of the navy. Even a “master carpenter” had the functional rank of a petty officer, not even that of a commissioned officer. By the 1700s, the term “carpenter” was replaced by “constructor,” and in 1717 the chief constructors were allowed to take the title *sieur* (esquire), the lowest rung of landed gentry, which allowed them to associate on social terms with naval officers, scientists, and some of the lower-ranking political figures.²⁶ This widening of their professional circles gave them a more expansive view of their work as shipbuilders; instead of simply looking at the ships as objects to be constructed and repaired, they understood more of what naval officers thought about them as they served aboard or sat on construction councils; what administrators considered when they prepared their navy budgets; and which scientific developments might have an impact on the way they designed and built their ships. In turn, these officers, administrators, and scientists were afforded the opportunity to better understand the people and processes behind naval construction, and even to develop a trust of sorts.

Maurepas was given to providing additional titles that denoted higher social status (e.g., allowing all constructors, not just chief constructors, to be called “esquire”), at the same time suppressing terms, such as “master” constructor, which denoted manual labor. However, he did not agree to a request by the shipbuilders to give them an honorary title and rank such as commissioner or engineer, which they argued was done in other countries.²⁷ That title and rank did not come until the 1765 ordinance, which effectively put members of the Corps of Engineer-Constructors on the same social footing as officers in the navy and in the Corps of Military Engineers, and even granted them their own military uniforms.

All new members of this corps had to graduate from Duhamel du Monceau’s school, which was officially sanctioned and given the new title *École des Élèves Ingénieurs-Constructeurs de la Marine* (School of Student Engineer-Constructors of the Navy). A cadre of instructors, some from the Academy of Sciences and others from the dockyards, were employed to teach the curriculum, which consisted of mathematics (calculus in particular), mechanics, physics, and graphic design, as well as theory of ships. In addition to the original texts by Duhamel du Monceau and Bouguer, a number of new texts were added to the curriculum, including the unauthorized edition of Euler’s *Théorie complète de la construction et de la manoeuvre des vaisseaux* and a translation of Chapman’s *Tractat om skepps-byggeriet*, followed by a translation of Juan y Santacilia’s *Examen marítimo*. Typically only two or three students were admitted each year, after

passing an examination at age 16. They initially spent two years in a dockyard and then another two to three years in the school, which had between two and ten students at any given time. They were admitted as junior constructors only after passing another examination that included the complete design of a ship and its accompanying calculations, which were reviewed by a senior constructor. Junior constructors typically spent six months at sea before working at a dockyard. After a few years, they could pass another examination—basically, a ship design and set of calculations approved by a senior constructor—to become an “ordinary constructor,” at a pay of 2,400–3,000 *livres tournoises* annual salary (about \$16,000–\$20,000 in 2002). The best went on to become inspectors general.²⁸

The School of Student Engineer-Constructors of the Navy was directed by Duhamel du Monceau until his death in 1782, although its day-to-day functions were overseen by a governor. For two years the school was without a director and in danger of closure, until the appointment in 1784 of Jean-Charles de Borda.²⁹ In 1786 the school was opened up to student constructors from merchant yards and student civil engineers who would go on to build port facilities such as drydocks and quays.³⁰

The French Revolution, which began in 1789, had enormous consequences for the development of ship theory and the professionalization of constructors. A growing anti-academic movement among the leaders of the Revolution resulted in the closure of the Academy of Sciences in August 1793, followed by the guillotining of a number of prominent members for their previous political connections. Most of the scientists and engineers who were engaged in the development of ship theory were associated with or supported by the Academy; its closure effectively stopped almost all new efforts in that field, and there would be almost no original work on the subject published in France for 20 years.³¹ The School of Student Engineer-Constructors of the Navy, considered an annex to the Academy, was also closed. At the same time, the Committee of Public Safety, as the directing body of the Revolution was called, established several new schools, including the *École Centrale des Travaux Publics* (Central School of Public Works), which in 1795 became the *École Polytechnique* (Polytechnic School).

Borda was allowed to reopen the constructor's school in 1795 under the name *École des Ingénieurs des Vaisseaux* (School of Vessel Engineers), but as an “application school” that select students of the *École Polytechnique* would attend after their initial studies. This was a watershed in the professionalization of naval constructors; for the first time, they were considered “engineers” not just in title, but also in education and formation. Naval constructors would share the same basic schooling in mathematics and sciences as other military and civil engineers before going on to the School of Vessel Engineers for further education in naval architecture. In keeping with the

revolutionary spirit, the school was not in the Louvre but in a house on rue Saint-Dominique, on the site of the present-day Ministry of the Army. In 1799, the constructors were renamed the Corps du Génie Maritime (Corps of Maritime Engineering), the title they would carry until the twentieth century, and the school was renamed École Spéciale du Génie Maritime (Special School of Maritime Engineering), before the curriculum was folded into the “grandes écoles” system in the 1970s.³²

Borda, who during the Revolution was the leader of the commission that developed the metric system, died in 1799. The post of director of the school was briefly taken by Jean-François Gautier, the constructor who had set up Spain’s Corps of Naval Engineers in the 1770s and had then returned to France. When Gautier died in 1800, after just one year in office, the constructor Honoré-Sébastien Vial (du) Clairbois³³ took over the school, oversaw its move to Brest in 1801 and led it until his retirement in 1810. France’s conquests in Europe (principally under Napoleon) from 1792 to 1801 had brought dockyards in the Netherlands, Genoa, Naples, and Venice under its effective control, and foreign constructors were sometimes sent to the Special School of Maritime Engineering for their formation and education. The school was moved from Brest to the former Dutch port of Antwerp (Anvers in French) in 1810, then to Toulon in 1814 as Napoleon’s empire crumbled.³⁴ It would be moved and change names several more times, but by then the French Corps of Maritime Engineers had become the model for the new wave of professional corps of constructors that evolved throughout Europe during the 1800s, and the School of Maritime Engineering would serve as a model for naval architecture curricula around the world.

Spain’s Corps of Naval Engineers

Family ties between Spanish and French royalty, as well as a growing necessity to integrate its armed forces against the British, led to Spain’s increasing adoption of French models for its own institutions. As in France, the professionalization of Spain’s naval constructors had its origins in the Corps of Military Engineers and Navy Guards. In 1711, Jorge Próspero de Verboom, engineer general of the Spanish forces, established the Cuerpo de Ingenieros (Corps of Engineers) along the lines of his colleague Vauban’s Corps of Engineers.³⁵ In 1717 the Italian-born intendant general of the navy (later secretary of state) José Patiño Rosales created the Real Compañía de Caballeros Guardiamarinas (Royal Company of Navy Guards) in 1717, which was based principally on Colbert’s Gardes de la Marine. The Academy of Navy Guards at Cadiz had a curriculum in mathematics, fortifications, navigation, and naval construction, often taught

by Jesuits. Several other schools for pilots and navigators were established, such as the College of San Telmo in Seville.³⁶

The most famous of the Navy Guards were Jorge Juan y Santacilia and Antonio de Ulloa y de la Torre-Guiral, who were plucked out of the Academy of Navy Guards in January 1735 and sent to Peru on the geodesic mission, returning to Spain in 1745. In 1751 Juan y Santacilia became commander of the Navy Guards. At the same time Louis Godin, also returned from Peru but barred from the French Academy of Sciences for his failures as leader of the geodesic mission, was appointed director of the Academy at the urging of his former companion Ulloa.³⁷ Later, the post of director was given to a distinguished constructor and mathematician, Gabriel Ciscar y Ciscar, who would subsequently participate in the international commission on metrification that was pioneered by Borda.³⁸

The first formal steps toward standardization began without any recourse to the use of ship theory, a curious fact, given that this standardization began under Jorge Juan y Santacilia in 1752. He was sent to Britain in 1749 by first Minister Zenón de Somodevilla y Bengoechea, marquis of Ensenada, to spy on military installations around the country and examine naval construction. Taking the name “Georges Josues” (a Portuguese Sephardic name), Juan y Santacilia set himself up as a London bookseller, and despite his alias, he was made a member of the Royal Society under his correct name.³⁹ Although he gained intimate knowledge of many important details of British construction techniques, his greatest coup was to recruit and secretly transport almost 70 British and Irish naval technicians—constructors, sculptors, caulkers, and others—to work in the shipyards of Spain and Cuba.⁴⁰

Shortly after his return to Spain in 1750, Juan y Santacilia was appointed by Ensenada to oversee naval construction, in effect becoming chief constructor. He set up the Junta de Constructores (Council of Constructors) in Madrid, bringing together the principal constructors of the major dockyards—Cadiz, El Ferrol, and Cartagena—to study and decide upon a common set of characteristics for the ships. He was strongly influenced by the British system, which relied on a fairly tight centralized control of design and construction through the chief surveyor, but where ship theory played no part. The Council of Constructors was short-lived, for Ensenada fell from power in 1754, effectively removing the authority granted to Juan y Santacilia. Nevertheless, the Council’s influence was felt long afterward; Jorge Juan’s experience in Britain, along with the collective knowledge of expatriate constructors such as Edward Bryant and Richard Rooth, had enabled the Construction Council to establish a set of rules called *construcción a la inglesa* (English-style construction), marked by wider hulls,

lighter framing, and stronger connections (e.g., heavier beam knees) compared with previous Spanish construction. A number of standard-design ships were built to these rules between 1754 and 1773, including the series of 74-gun ships that became known as the “12 Apostles,” named for the first few ships of the series, such as *San Pedro Apóstol*.⁴¹

Although Juan y Santacilia would later write *Examen marítimo* (Maritime Examination), one of the great works of naval architecture, it appears that he did not employ any theoretical calculations in establishing these rules. As described in chapters 3 and 4 of this book, he correctly believed that these theories were either wrong or too incomplete to be of any practical use. This would change with the arrival of French constructor Jean-François Gautier, brought from France in 1765 to help consolidate the French and Spanish fleets after the signing of the Third Bourbon Family Pact by Choiseul and his counterpart Jerónimo Grimaldi. Gautier was in fact a fairly inexperienced constructor, having built only one ship (the 64-gun *Provence*), and had recently competed (unsuccessfully) for the 1765 French Academy prize on lading and ballasting.⁴² Despite this lack of experience, Gautier (Gautier Audibert in the Spanish patronymic-matronymic) was placed in charge of instating a system of standardization like that under Choiseul’s 1765 ordinance. Gautier’s approach to design and fabrication favored length and speed, and had fewer strengthened connections, such as deck knees, which made the ships cheaper and faster to build. In 1767 the navy adopted Gautier’s plans as the standard for all ships, over the objections of Juan y Santacilia and the British-born constructors who believed (correctly) that the designs were less stable and generally weaker than the English-inspired designs. But Minister of the Navy Baylio Frey Julián de Arriaga y Rivera, who had succeeded Ensenada, wanted precisely what Gautier was offering—fast ships that could be built quickly and inexpensively, to counter the enormous British fleet.⁴³

Gautier was promoted to director general of construction in 1769, a normally honorific post that in fact gave him great authority. His principal task was to create the Cuerpo de Ingenieros de Marina (Corps of Naval Engineers) and an academy based on the French Engineer-Constructors of the Navy, established just a few years earlier. In 1770 the Corps was put into place, and in 1772 the Academia de Ingenieros de la Armada (Academy of Engineers of the Navy) was established in El Ferrol. Its curriculum emphasized practical knowledge as well as theory; some student constructors, in fact, took their practical formation into other careers, such as metallurgy. In 1776 a new ordinance was published that, like Choiseul’s 1765 ordinance, firmly established the career path of the constructors and the technical information required to be included on ships’ plans, including displacement and stability calculations.⁴⁴

Gautier did not stay long enough to see the apogee of Spanish construction. Although he was nominally the supervisor of all constructors, he was unable to get other constructors to obey his orders, and the ordinances that he drew up were ignored. He applied to be relieved of his post several times, and was finally allowed to return to France in 1782. There he was soon made director of construction of the Toulon dockyard; in 1799 he became director of the Special School of Maritime Engineering in Paris, a post he held until his death in 1800. In Spain, José Romero Fernández de Landa, a friend and protégé of Juan y Santacilia, took over the Corps of Naval Engineers and became director general of construction; he instated a series of reforms to consolidate and strengthen the formation and structure of the Corps, reintroduced a more “Spanish” type of construction that improved the strength and stability of ships (most famously the 74-gun *San Ildefonso*), and carried out sea trials to correlate the operating characteristics of the ships with their technical data, such as displacement, stability, and sail plan.⁴⁵

Romero Landa continued in his post until 1807, but the power of the post had been much diminished since 1791, when Julián Martín de Retamosa, a naval officer and not a constructor, had several successful ships built to his designs, most notably the *Montañés*, modified from Romero Landa’s *San Ildefonso*. In 1793 Retamosa was placed in charge of dockyards and construction, and became a vice admiral in 1802. He took over as director of the Corps of Naval Engineers after Romero Landa, but the Corps was already on the decline after the defeat of the combined Spanish and French fleet at the battle of Trafalgar in 1805. The number of constructors gradually diminished during the French occupation of Spain from 1808 to 1814, and even after the return to power of the Spanish monarchy under Ferdinand VII, the navy was almost ineffective, contributing to the loss of Spain’s empire in Latin America during the 1810s and 1820s. The last engineer was admitted in 1819, and the Corps of Naval Engineers was formally abolished in 1827.⁴⁶

Denmark’s Naval Officer-Constructors

Never larger than about 45 ships, compared with the hundreds of ships in the British and French navies, the Danish navy always had to do more with less. Unlike most other European navies, in which constructors and naval officers had separate careers under different authorities, the Danish navy’s constructors were part of the officer corps. Since the late 1500s, Denmark’s ships were built principally by foreign-born constructors such as Francis Sheldon from Britain.⁴⁷ In 1690, a policy of nationalization of shipbuilding was begun, with Admiral Henrik Span (himself of Dutch origin)

put in charge of construction. Span hired the young mathematician Olaus Judichær as his assistant, and the latter quickly rose to chief constructor in 1691. At the same time, Denmark's shipbuilding capability was greatly increased with the expansion of the Holmen naval base just outside the Copenhagen city walls.

In 1701, the Søkadetakademiet (Naval Cadets Academy) was founded in Copenhagen to train all future naval officers. The instructors were generally naval officers with a strong background in both theory and practice—Judichær became the first instructor of ship construction—additional lectures were given by mathematics professors such as Christen Hee and Thomas Bugge. In 1727 the Academy was moved into a former opera house on the Fredericiagade (today the Østre Landsret [Danish High Court]), where navy and army cadets were trained side by side. Cadets were accepted at between 14 and 18 years of age, and learned a wide range of subjects, including tactics, navigation, and construction. The most skilled cadets were chosen to become constructors, and attended the Board of Construction, which oversaw Danish naval shipbuilding. They were then sent overseas for several years to learn construction techniques in Britain, France, Sweden, Russia, and the Netherlands, since this period was one of relative peace between Denmark and those nations.⁴⁸

Industrial espionage was considered part of the constructor's practical formation, in much the same way that Danish ship officers would often serve in other navies for training purposes. The former cadets would be assigned to travel in pairs to dockyards and installations specifically targeted for their perceived dominance in certain areas. They obtained a large amount of technical information in the form of drawings and on-the-spot sketches, and made many important contacts during these trips that served them well during their tenure as constructors. As mentioned in chapter 4, Frederik Wegersløff met Leonhard Euler in 1734 and corresponded with him about stability, later returning to teach mechanics and hydrostatics at the Naval Cadets Academy until 1741. Frederik Michael Krabbe met with Pierre Bouguer and Duhamel du Monceau during his visit to France in 1754. Even though Sweden, and Denmark were former adversaries and uneasy neighbors, Henrik Gerner met Fredrik Henrik af Chapman in the 1760s, and his later student and successor Frantz Hohlenberg studied under Chapman. As a result of these foreign tours, Denmark possessed one of the largest collections of ships' plans from France, Britain, Sweden, and the Netherlands, which naval historians continue to use to this day.⁴⁹

Although Danish naval officers were ostensibly the constructors and carried out the calculations, professional draftsmen drew the actual plans under their guidance. A "construction school" for dockyard draftsmen, established at Holmen in 1757, pro-

vided draftsmen with a formal education in construction similar to that received by naval cadets, though without the courses in, for example, tactics and navigation, required by a naval officer. Draftsmen could not rise to the level of chief constructor, although they would sometimes act in that capacity when independently carrying out a complete design (e.g., Anders Turesen, who built several frigates and ships of the line).⁵⁰

Other Navies

From the late 1700s through the 1800s, many European navies followed the examples of France, Spain, and Denmark to develop systems of professionalization for their constructors. These were generally based on the French model of a constructors corps separate from regular naval officers; in most cases members were civilians, but in Sweden, they had military status.

Sweden's Fleets Constructor Corps

Swedish constructors had been civilian employees of the navy since the 1600s. After Fredrik Henrik af Chapman retired in 1793 with the rank of vice admiral (he was the first Swedish constructor to be given military rank), he set about creating a professional corps of constructors to replace the existing system. In his original plan there were two small corps, one for the inshore fleet and the other for the high seas fleet. The constructors were given military rank, similar to those of Swedish military engineers, although they were not full naval officers, as in the Danish system. In 1798 the two corps were merged into the Fleets Constructor Corps (Flottornas Konstruktionskår) with a central office in Stockholm; its naval uniform included the metacenter button shown in figure 4.1.

In 1804 Chapman revised the curriculum for the candidates to include theoretical training in mathematics, mechanics, and ship theory, followed by practical experience in dockyards. Naval officers bound for the high seas fleet also received extensive training in naval architecture. The nominal textbook for the course was Chapman's *Tractat om skepps-byggeriet* (Treatise on Shipbuilding), and other material was written by the instructors themselves. From 1824, when the two fleets were merged, the Corps became the Fleet Constructor Corps (Flottans Konstruktionskår) or simply Constructors Corps (Konstruktionskåren). In 1867, during a major naval reform, the Corps was merged with the steam engineers' Machinist Corps (Machinstkåren) to become the unified Corps of Naval Engineers (Mariningenjörskåren).⁵¹

Britain's Constructors

Britain's naval and commercial shipyards, like many others around Europe, operated on an apprentice system to train its constructors. As in other guilds, an apprentice would pay his wages to a shipwright for around seven years in order to learn the trade. Normally, only boys from wealthier families could afford to be apprenticed to the master shipwright and his assistant, the only ones who could teach the entire process of ship design and construction, including the requisite geometry and arithmetic.⁵² Each shipyard was its own guild, and shipwrights had no external organization. For example, the Worshipful Company of Shipwrights, a charitable organization founded before 1387 that existed principally to provide a "safety net" for families of the members, did not count many of the master shipwrights in its ranks.⁵³ Given that this system worked reasonably well, there was no perceived need to change the guild system in favor of more formal classroom instruction and training.

A significant factor that may have held back any British interest in developing a long system of professionalization was the fact that many warships—up to half the total in some years—were built under contract in commercial shipyards and not in government dockyards, although a navy surveyor oversaw construction. France and Spain, not having anything like the extensive network of commercial financial markets available to private British shipbuilders to underwrite costs, relied almost exclusively on government dockyards for their fleets.⁵⁴ Since those dockyards were completely under government control, it was comparatively straightforward to create a seamless system of professional formation and incorporation of ship theory across the whole of naval construction. In Britain, the financial pressures on private yards to build ships on schedule and within budget would have precluded any such scheme of professionalization. Government dockyards could not have afforded the delays from incorporating naval architecture into their designs, as they were effectively competing with commercial shipyards.

Thus, the structures of standardization and centralization had been put into place well before any ship theory was being developed or any system of professionalization was put into place, and had to be adapted to both government and commercial shipyards. The British navy was producing what were arguably the most successful warships on the planet, winning the majority of engagements and capturing five times as many enemy ships as its nearest rival, France—all without the benefit of the meta-center or the calculus. Therefore, when British naval officers excitedly remarked on the new theoretical developments coming from France, or on the system of rigorous technical schooling for French and Danish constructors, the response from British constructors would understandably have been, "So what?"

Change, as always, was inflicted on the constructors for bureaucratic rather than technical reasons, although it would be many years before a system of professional formation and a centralized corps of constructors would become established. By 1800, the apprentice system was seen to be corrupt due to its reliance on fees paid to a master (i.e., wealthier students would receive better education than more deserving but poorer ones), and therefore in need of overhaul. The inspector general of the navy, Samuel Benthams, also believed that apprentices needed more instruction in the skills required for naval construction. He instated a new system of apprenticeship in 1802 that abolished the payment of apprentice fees to the shipwrights and, separately, established an educational system for mathematics and naval architecture. The scheme failed almost immediately; a major source of income for the shipwrights—apprenticeship fees—dried up, so almost no new apprentices were taken on. As part of a general overhaul of naval dockyards established by Parliament, the Commission of Naval Revision set up by Charles Middleton, Lord Barham (a determined advocate of reform since the 1770s, he was one of the founders of the Society for the Improvement of Naval Architecture and an early believer in “scientific” ship design), recommended in 1805 that a two-tier education system be created: a dockyard school for shipwright apprentices, and a seven-year school of naval architecture (with competitive entrance exams) for constructors. The dockyard school was never established, but the School of Naval Architecture was opened in 1811 at the Royal Naval College in Portsmouth. However, because graduates were immediately put in charge of experienced shipwrights at dockyards without having first learned the practical skills, they were uniformly ignored and despised. The school stopped accepting applicants in 1822 and closed in 1832.⁵⁵

After another aborted attempt in 1848–1853, the permanent School of Naval Architecture was finally opened in 1864 in Kensington, London, in what is now the Henry Cole Wing of the Victoria and Albert Museum; it was merged with the Royal Naval College at Greenwich in 1873 (and moved to University College London in 1968). After a series of difficulties in adopting new technologies of steam and iron, and following the capsizing of the low-freeboard turret ship HMS *Captain* in 1870, due to faulty calculations and a mistrust of Admiralty constructors, the British navy was ripe for a professional construction corps based on the French Corps of Maritime Engineers. In 1883 a proposal by the constructor William White was adopted, and the Royal Corps of Naval Constructors (RCNC) was created, with a rigid system of theoretical and practical formation at the Royal Naval College and a uniformed branch equivalent in rank to naval officers.⁵⁶ The RCNC, based on the system that Duhamel du Monceau created in 1765, would serve as the model for many other navies’

constructor corps, such as those of the United States and Canada. The School of Naval Architecture would also form the basis for similar departments at universities in many countries.

Netherlands Constructors

The Netherlands navy was closely allied with the British navy through much of the 1700s, and employed several British constructors in its dockyards from the 1720s. The navy was divided into five regional administrations—the largest being Amsterdam and Rotterdam—each with its own dockyard and internal apprenticeship program. The centralization of the Dutch navy did not begin until the Batavian Revolution of 1795, during which the Batavian Republic was formed and allied itself with the French Revolutionary government. With the new Republic now at war with Britain, shipbuilding was centralized under the Rotterdam constructor Pieter Glavimans, and from 1795 until 1810 all the designs were his. In 1806, when the Kingdom of the Netherlands was formed under Napoleon's brother Louis, Glavimans sent his son Pieter the younger to study naval architecture, first under Sané in Paris and then at the Special School of Maritime Engineering in Brest under Vial du Clairbois. Cornelis Soetermeer followed him in 1809, and six other Dutch students came in 1813, although by then the Netherlands was part of France and the school had been transferred to Antwerp. These students eventually became some of the leading constructors in the Kingdom of the Netherlands that formed after the demise of Napoleon. The School voor de Genie der Marine (School for Naval Engineering), based on the French model, was established at Rotterdam in 1822 by one of the French-trained students, Cornelis Jan Glavimans, but the Korps Ingenieurs der Marine (Engineer Corps of the Navy) was not formed until 1843. A curriculum for naval architecture was established by the navy at the Technical University of Delft in 1869.⁵⁷

Venice School of Naval Architecture

In hindsight, it is curious that Venetian administrators were so late to impose ship theory on constructors. From 1525 to 1529, a professor of Greek oratory, Vettor Fausto, reconstructing ancient Greek ideals of ships, convinced the Senate to build galleys with four and five rowers per oar, which proved to be marginally faster than the standard three-men-per-oar then in use. The story evolved that Fausto succeeded because he was able to use Aristotle's mechanics of the lever in the design of the oar systems.⁵⁸ Perhaps emboldened by this story of the utility of mechanical theory, in 1593 the Venetian commissioners asked the eminent scientist Galileo Galilei for technical

advice on the position of oars; although his ideas turned out to be faulty, the problems of the strength of oars gave him crucial insights in his early development of beam theory.⁵⁹

It was only much later that Venetian administrators, through their close ties with France, came to appreciate the utility of ship theory in design. As described in chapter 2, in 1764 they were among the first to try Bouguer's experiment to determine the center of rotation on the 64-gun *San Carlo Borromeo*. They also copied French ships, starting with two frigates in 1767. In 1772 the Senate authorized the erection of a model hall (*sala da modellar*) within the Arsenal to create and store ships' plans and models. At the same time it contracted with the architect and mathematician Gianmaria Maffioletti to develop a curriculum of naval architecture instruction, which was begun in 1774 and was finally approved in 1776.

The Scuola di Naval Architettura (School of Naval Architecture) was opened in the model hall in March 1777 with instruction by Maffioletti, the hydraulics engineer Šimun Filip Stratik (Simone Stratico), and a professor named Luigi Fabris. Student constructors would enter at age 14 to 20, and take four years of theoretical education in mathematics, mechanics and ship theory, followed by a fifth year of practical instruction. Translated works of Euler, Bouguer, and Juan y Santacilia were the texts for the school. Graduates were given the title *architetto* (architect), as distinct from the *proti* (shipwrights), who had no theoretical training. However, in contrast to the French model of professionalization, the architects did not form a distinct corps of constructors because they were concentrated in one dockyard and thus already possessed a centralized body of control.

In the event, the school was short-lived. Only four groups of students graduated before the French invasion of Venice in 1797 (it then came under Austrian rule). Maffioletti died in 1802, before the fifth and last group graduated. The school did not survive much longer than its founder; it appears to have gone out of existence around 1806, when Venice was removed from Austrian control by Napoleon. Until 1814, French constructors such as Pierre Forfait and Jean-Marguerite Tupinier oversaw the building of warships for the French navy, although Italian constructors such as Andrea Salvini and Giuseppe Moro (both graduates of Maffioletti's school) actually carried out the work.⁶⁰ Naval architecture education continued in places such as Trieste, where in 1816 Giuseppe de Volpi created a curriculum at the Accademia di Commercio e Nautical (Academy of Commerce and Nautics) that was eventually restructured and taught by Salvini's nephew Gaspare Tonello from 1819 to 1849.⁶¹

Professionalization: A Summary

Beginning with the French and Danish schools and corps that first appeared in the 1700s, navies and nations around the globe would, by the late 1800s, put into place their own systems of professionalization that would include networks of university departments of naval architecture and elite corps of naval constructors. Naval constructors came to be seen as socially elite professionals and not lay workers. Even their offices bore the stamp of at least the lower rungs of aristocracy; figure 6.4 shows the Danish constructor Diderich Lauritsen de Thura at work in comfortable surroundings, including a stove, full-length mirror, and velvet curtains. Naval architecture itself would come to be seen at the forefront of engineering theory and practice, and the great passenger liners and battleships that the constructors went on to design and build would arguably be the most complex engineering structures of their day. The



Figure 6.4

Danish naval constructor Diderich Lauritsen de Thura in his office (1752). Credit: Royal Library of Denmark.

ability of the constructors to operate at the leading edge was due less to the naval architecture theories they employed, and more to the rigorous education and career formation that gave them a theoretical and practical basis for the sound engineering judgment required to succeed.

Conclusion: Naval Architecture at the End of the Scientific Revolution and the Beginning of the Industrial Age

It was inevitable that the development of naval architecture, like other areas of engineering, would move from the world of scientific academies to that of practical constructors. This trend had been forming since the 1760s, when the major strides in ship theory made by scientists with no hands-on experience (Bernoulli, Bouguer, Euler) began to give way to theory development by practical but learned constructors (Juan y Santacilia, Chapman). Two separate events in the early 1790s hastened that transition, marking the end of one era for naval architecture and the beginning of another: the closure of the French Academy of Sciences and the opening of the Society for the Improvement of Naval Architecture. The first event signaled the end of state-sponsored research into ship theory, and its use by governmental bureaucracies, that was indicative of its place in the Scientific Revolution; the second marked the beginning of investigations by independent engineers as a means of optimization and practical problem-solving for meeting specific commercial demands, that became the hallmark of the Industrial Age. In rather simplistic terms, at the transition from the eighteenth to the nineteenth century, naval architecture made the leap from French scientists in the burned-out Scientific Revolution, across the Channel to the British engineers working at the dawn of the Industrial Age.

The Closing of the French Academy of Sciences

In continental Europe, the French Revolution caused the closure or disruption of almost all scientific academies from 1792 to 1815, as the French Revolutionary and Napoleonic Wars raged across the continent. The French Academy of Sciences was closed by public decree on 8 August 1793, then was reconstituted in 1795 under the Institute of France. The French Academy of Navy in Brest, closely linked to the Academy of Sciences, also closed in 1793. The execution of the French chemist Antoine de Lavoisier in 1794 was accompanied by the famous (though probably apocryphal) statement, "The Revolution has no need of scholars." This sent a chill throughout the French scientific community, and many academicians were pressed into politics at the expense of their research.⁶² Scientific publishing, which had been on

the rise since the 1780s, dropped precipitously by the turn of the century and did not recover until 1817.⁶³

In principle the scientific academies in the rest of Europe continued to function, but in practice many were already in decline by the 1790s, and the constant warfare until 1815 greatly curtailed their activities. The Saint Petersburg Academy, which had hosted Leonhard Euler and Daniel Bernoulli, virtually went out of existence after the death of Catherine II (the Great) in 1796, and would not be fully reestablished until the 1860s. The Berlin Academy, where Euler and the Bernoullis made great contributions, suffered after the death of its patron Friedrich Wilhelm II in 1797, and after several administrative changes was finally made part of the University of Berlin in 1812. The Swedish Academy had, by 1783, turned its attention to practical matters such as agriculture and trade, and would not reemerge as a strong fundamental science institution until the reforms of Jöns Jakob Berzelius in 1821. Only in Britain did the Royal Society (which was not a government entity) continue to function as before, although even it suffered a decline in activities until the 1840s.⁶⁴

The Society for the Improvement of Naval Architecture

As noted earlier, many British naval officers and administrators believed that French ships were superior sailers. Listening to their conversations, John Sewell, the publisher of the widely read periodical *The European Magazine and London Review*, came to believe that a lack of “scientific” naval architecture was holding back Britain’s navy and merchant fleet. He stated his case on the blue wrapper of his magazine, arguing that French ships were faster than British ships because they employed scientific principles.⁶⁵ This led him to form the Society for the Improvement of Naval Architecture in 1791, aiming to provide a central location for the dissemination of scientific knowledge in ship design. The Society was noteworthy as one of the first independent professional engineering societies, preceding the Institution of Civil Engineers (created in 1818) by a quarter-century. Its members included such luminaries as the scientist Joseph Banks and the duke of Clarence, the future King William IV.⁶⁶ Although short-lived, the Society sponsored a series of resistance experiments by Mark Beaufoy (discussed in chapter 3) that would find practical use by Robert Fulton in developing early steam-and-paddlewheel engines, and later by Isambard Kingdom Brunel and John Scott Russell in their designs for the *Great Britain* and the *Great Eastern*.

Another indication of the leap of naval architecture from France to Britain, and from government support to private achievement, were the two papers by Atwood and Vial du Clairbois, presented to the Royal Society in 1796 and 1798 (and reprinted by Sewell’s Society), on the inclination of ships at large angles of heel (discussed in

chapter 4). These papers marked the first substantial advances in stability theory since Bouguer's explanation of the metacenter in 1746.

The Transition of Naval Architecture from the Eighteenth to the Nineteenth Century

By the end of the eighteenth century, the era of "big science" conducted by state-sponsored institutions such as the French Academy of Sciences had drawn to at least a temporary close, and with it the great creative experiments of the Scientific Revolution also ended. In hindsight, this era could be seen as laying the groundwork for practical developments that would occur in the nineteenth century, such as the use of chemistry and thermodynamics in the harnessing of steam, and the theories of mechanics for the new iron structures.⁶⁷ But of course the engineers and scientists of the eighteenth century had not thought this way; they certainly believed that their theories could become immediately useful, as did the academies and the patrons who funded them. In fact, ship theory did come to be applied to a limited number of practical problems, such as Bossut's hydrodynamic evaluation of the Picardy Underground canal and Chapman's "relaxation method" of hull construction (chapter 3), as well as the inclining of *Royal Louis* to assess its refit (chapter 4).

In rare cases, independent merchant constructors would apply theory as a means to optimize their designs, such as the Trieste constructor Odorico Panfilli adopting the bow of least resistance (mentioned in chapter 3). But these calculations could take months to complete, cutting into the building schedules, increasing costs, and delaying the moment a shipowner obtained his vessel to start turning a profit. More important, the formation of a constructor to perform these calculations would occupy several years of his working life, incurring costs in addition to lost revenue while he was in school. These expenses were simply not justifiable in terms of profitability, given that the resulting ships were not markedly faster, more maneuverable, or more stable.

Rather, the systematic use of ship theory made sense only within the educational and administrative infrastructures established for naval construction. In the world of naval construction, ship theory was important, not so much as a means of solving problems or optimizing designs but as way of controlling the constructors and the ship design process. Naval administrators exercised control by insisting that specific calculations—metacenter, ratio of bow resistance, and the *point vélique*—be carried out during ship design; in that way, they could be reasonably confident that their constructors would carry out the calculations, and that the resulting ship would be satisfactory. However, during the eighteenth century there was no indication that

constructors of any nation routinely used ship theory to conduct experiments, either on paper or at small scale, in order to optimize designs or to avoid expensive full-sized mistakes. All calculations that I have seen were done just once and submitted with the plans, without any revisions or suggestions for improvements that would have pointed toward a modern concept of engineering as a tool for optimization. Because constructors had no measurable criteria to design to—the metacenter should be this high, the ratio of bow resistance should be greater than that value—they had no reason to revise their designs based on those calculations. Constructors submitted those calculations because they were required to do so. Any measurable improvement in stability, speed, or seakeeping as a result of those calculations was more likely the result of chance than of design.⁶⁸

By contrast, the development of naval architecture in the nineteenth century would become dominated by economic concerns of private companies, especially to make the most cost-effective use of the new technologies of iron hulls and steam power. Governments at first played a relatively minor role in this, and in fact depended on private enterprises for their developments of these new technologies. Certainly by 1800, constructors across Europe and in North America understood the basis for calculating stability, hydrodynamics, and maneuvering characteristics. It is probable that most of them, by that time, recognized that they lacked a system of acceptance criteria for those theories to judge whether a design was adequate or not. In the case of hydrodynamics, they even lacked instruments such as the dynamometer in order to evaluate resistance. The basic analytic understanding had been developed during the previous century, and what was now needed was the practical experiments and instrumentation that could put quantifiable numbers into those mathematical frameworks.⁶⁹ But as iron and steam technologies came into more widespread use, and competitive pressures drove shipowners to bigger and faster vessels, the tried-and-true rules of thumb became increasingly inadequate. For example, how much $\overline{GM}$ was required for initial stability? What should the GZ curve look like? What constituted excessive roll motions? How much power did the ship require to make 10 knots? The answers to these questions were slowly filled in during the next century, as constructors—very often British, since by 1815 that nation controlled the world's oceans—sought to solve these practical engineering problems through the patient accumulation of data and the development of theories that owed more to observation and empirical data than to fundamental principles of mechanics.

This quest for accuracy in data collection, and use of it in building theoretical models to develop and validate engineering judgments, would be embodied in the British civil engineer Isambard Kingdom Brunel. Brunel would extend his previous

experience in railroads and bridge construction to create increasingly larger ships—*Great Western*, *Great Britain*, and finally *Great Eastern*—from 1835 to his death in 1859. To confirm the adequacy of these ships to ply the oceans, he would draw to himself the knowledge and experience of ship constructors such as John Scott Russell and civil engineers such as William Fairbairn and William Froude, who over the next half-century would themselves develop the new theories, methods of measurement, and fundamental criteria for structural strength, stability, and ship resistance that would form the basis of modern naval architecture.⁷⁰ Navies would at first draw upon this commercial experience to assist them in their own developments of these new technologies; for example, Brunel's work on the screw propeller played a major part in the British navy's decision in the 1840s to adopt it over the paddlewheel. By the end of the nineteenth century, however, those navies would establish a system of model basins and other test facilities that would bring development and use of ship theory squarely back into the government domain. Science and naval architecture would come to play a vital role in the evolution of doctrine and naval technology as twentieth-century navies sought competitive advantage over enemy fleets with faster, more survivable, and (later) stealthier ships.

Of all the ship theories developed during the 1600s and 1700s, such as the *point vélique* and ratio of bow resistance, only the metacenter would survive until the present day. It is the university curricula of naval architecture, with their roots in Duhamel du Monceau's Little Navy School, and the professional corps of constructors in navies around the world that trace their beginnings to the French Génie Maritime, that remain as the lasting legacy of naval architecture in the Scientific Revolution.⁷¹

Epilogue: Promised Land

On Bouguer's return from Peru, he published *Traité du navire*. Several years later, he became involved in open conflict with a colleague from the Geodesic Mission, La Condamine, which cast a shadow over his many successes. This epilogue describes and analyzes the conflict, and portrays Bouguer in his final years.

The Figure of the Earth and the Quarrel with La Condamine

Bouguer had sailed into Nantes aboard *Triton* on 28 May 1744, carrying with him the manuscript of *Traité du navire* that he had brought down from the mountains of Peru and across the Atlantic. He stayed in Nantes at least a week, probably seeing his brother Jean in nearby Le Croisic. In June he returned to Paris, where he would spend the rest of his life. Eventually Bouguer moved into a house on the rue des Postes (today the rue Lhomond), near the Sorbonne, and was not far from the Louvre, which housed the Academy of Sciences and Duhamel du Monceau's Little Navy School, and was just a few minutes' walk from the publishing house of Charles-Antoine Jombert. Bouguer's teaching duties at Le Havre had long been filled by others, and in December 1745 he resigned his post as hydrography professor. From then on, he would earn his living as a member of the Academy of Sciences, although money would, as ever, be in short supply.¹

Bouguer's first task was to report to the Academy on the results of the Geodesic Mission, which he did from July 1744 until February 1745,² at the same time preparing *Traité du navire* for publication. Charles-Marie de La Condamine returned to Paris just in time to attend the last lecture, and shortly thereafter gave his own account. At this point, Bouguer and La Condamine appeared to be on good terms, and Bouguer's rise in the Academy seemed assured. In 1745 Maurepas appointed him to the Academy seat vacated by Maupertuis when he went to the Berlin Academy of Sciences. Bouguer, as nominal leader of the expedition after Louis Godin's disgrace, then took it upon

himself to publish what he considered the “official” history of the Mission, which became his 1749 book *La figure de la terre* (The Figure of the Earth). La Condamine did not oppose its publication, but when he wanted to publish his own account, Bouguer objected, on the grounds that he (Bouguer) was responsible for the overall accuracy of the observations. La Condamine’s accounts were eventually published over Bouguer’s objections in 1751, and became comparative best-sellers due in part to his enthusiastic (and less technical) style. La Condamine then tried to suppress Bouguer’s work, and though a commission was called in 1750 to settle the dispute, it went unresolved.³

The technical points of the dispute were petty, revolving around the choice of observations made by the members of the expedition; the quarrel had more to do with Bouguer’s vanity regarding his abilities as a mathematician and La Condamine’s desire to improve his social standing. Bouguer naively thought that the science should stand on its own merits, and he believed that a complete, technical reckoning of events should be enough to establish him as the true “hero” of the expedition. He made no effort to court the scientific elite, either in salons or in any other social setting. His patron, Minister of the Navy Maurepas, had been forced to resign in 1749, and Bouguer had no equally powerful supporter in the wings. La Condamine was far better connected—he counted the influential author Voltaire among his friends—and he was welcomed in social circles as a skilled storyteller. There was no question that La Condamine’s version of events would become more widely accepted. The dispute eventually moved from the floor of the Academy of Sciences to the public journals, which, though deploring the whole argument, generally avoided taking sides.⁴

However, the affair only served to damage Bouguer’s reputation as a scientist, derailing his rise within the Academy. He never quite attained the standing of other scientists, even though during the 1750s he had the most publications of anyone at the Academy.⁵ In retrospect, the quarrel was unnecessary—Bouguer had given La Condamine full credit in his own work, and La Condamine’s books were of a different style and did not dispute Bouguer’s conclusions—as well as unfathomable. As Condorcet noted in La Condamine’s eulogy:

One wonders what were the objectives of the dispute which arose between Bouguer and La Condamine, between two men who, during several years had slept in the same room, under the same tent, often on the ground, wrapped in the same blanket . . . all the time holding each other with reciprocal esteem.⁶

La Condamine, meanwhile, prospered as a result of his voyage and his retelling of his adventures; in 1760 he became one of the “forty immortals” of the Académie Française (French Academy), a seat he occupied until his death in 1774.

Bouguer's Final Years

Although Bouguer's standing in the Academy of Sciences was affected by his dispute with La Condamine, he continued to maintain extremely strong relations with the navy. The publication of *Traité du navire* in 1746 cemented his position as the premier scientific investigator in ship theory. He became an instructor at Duhamel du Monceau's Little Navy School, and a founding member of the Académie de Marine (Academy of Navy). Bouguer continued his theoretical explorations of naval architecture, writing six memoirs and another large book, *De la Manoeuvre des vaisseaux* (On the Maneuvering of Vessels). He did not neglect his other work, also writing a treatise on navigation as a follow-on to his father's work, and numerous memoirs on astronomy and geodesy, in addition to serving as judge on many commissions and Academy prize committees. In fact, his output was so voluminous that eight works were published posthumously.⁷ Bouguer also served as editor of the *Journal des sçavans* (Journal of Scholars). In 1751 he began a lively correspondence with Leonhard Euler, exchanging letters on a wide range of topics. However, the two men would never meet.⁸

Bouguer maintained good relations with many colleagues, especially the astronomer Nicolas-Louis de La Caille. It is not clear, however, whom he ever considered close, apart from his childhood friend Paul des Forges Maillard and his brother Jean (the latter died in April 1755).⁹ Bouguer never married, and there is no indication that he ever had a love interest. The personal circumstances of his final years are essentially a blank. He spent several days in the autumn of 1754 at the Loire château of Duhamel du Monceau's brother,¹⁰ but the rest of his correspondence is from his home in Paris and, according to Grandjean de Fouchy's eulogy, he spent most of his last years there.¹¹

In the end, Paris killed Bouguer. After surviving almost ten years in the harsh mountains of Peru, Bouguer was now living in the largest city in Europe, with all the amenities of civilization but with inadequate water that was polluted with sewage. It was a breeding ground for *Entamoeba histolytica*, a lethal species of amoeba that causes dysentery and liver infection. In the spring of 1758 Bouguer was attacked by what Grandjean de Fouchy termed a "blockage of the liver," what La Condamine said was an "abscess of the liver," and what La Caille called *hidropisie* (dropsy or edema), a fluid-filled swelling. These are all symptoms of amebic liver infection, which can take weeks or months to kill. At the time Bouguer was writing what would be his final work, *Traité d'optique sur la gradation de la lumière* (Optical Treatise on the Gradation of Light), his seminal work on photometry, and could barely get out of bed. He managed to finish the manuscript and take it a few blocks to the publishers Guérin and Delatour, but his strength was rapidly waning.¹²

On 23 July, Bouguer summoned the Dominican friar Pierre-Thomas Laberthonie, a well-respected preacher in Paris, to his bedside, but was so sick that Laberthonie could not come until 1 August. Over the following weeks, Bouguer had several extended discussions with him, which Laberthonie later wrote about in *Relation de la conversion et la mort de M. Bouguer* (Account of the Conversion and Death of Mr. Bouguer). According to his account, Bouguer presented several scientific arguments against religious “revelations”; however, the friar convinced him of the error of his ways, and Bouguer repented of those thoughts and converted. He received the last rites on 14 August, and at about 4 A.M. on 15 August 1758, Pierre Bouguer died.¹³

Bouguer’s estate was executed by La Caille, who oversaw the publication of *Traité d’optique* and took possession of his unpublished documents, which were eventually deposited in the archives of the Paris observatory (still not categorized). The little money he had, went to charity. The records of the original location of Bouguer’s grave are now lost, as a fire in the Tuileries in 1871 destroyed the Paris municipal archives. In the 1780s, however, all of Paris’s cemeteries were emptied and the bones removed to the now famous Catacombs. Bouguer’s mortal remains are now dispersed somewhere below the streets of Paris.¹⁴

Bouguer died without seeing the 1765 ordinance that would make his work on naval architecture a part of the fabric of the French navy. A poignant glimpse of Bouguer’s final months may be found in a letter written by a colleague, the mathematician Pierre Charles Le Monnier. Le Monnier was describing the results of an inclining experiment (discussed in chapter 4) on the 120-gun *Royal Louis* after a disastrous campaign off Brazil. Bouguer had evidently gone to see the ship in 1758, the year of its construction and of his death. Le Monnier stated:

M. Bouguer was the only one who foresaw the accident which happened to the *Royal Louis*, but he so little insisted, that his critics . . . and the ship’s constructors did not judge his research essential to their task.¹⁵

Once a proud, unwavering man, who in an earlier day would have certainly greatly “insisted,” Bouguer had diminished; one can almost see him, older and wearier, resigned to another fate. He knew he was dying; and perhaps he also knew that only the next generation would see the fruits of his labors, which would be forever denied him.

Appendix: Personages

Archimedes	Born: 287 B.C. in Syracuse, Sicily Died: 212 B.C. in Syracuse, Sicily	Mathematician; philosopher; engineer	Greatest mathematician of ancient times. Developed principle of buoyancy, wrote extensively on mechanics
Aristotle	Born: 384 B.C. in Stagirus, Greece Died: 322 B.C. in Chalcis, Greece	Philosopher	Philosophized on every subject of the ancient world, including mechanics
Atwood	Born: 1745 in London Died: July 1807 in London	Physicist	Specialized in studies on gravity and mechanics. Developed theory of stability for large angles of heel
Baker	Born: circa 1530 in Britain Died: 1613 in Britain	Constructor	Appointed master constructor under Queen Elizabeth I
Béldor	Born: 1693 in Catalonia, Spain Died: 8 Sep. 1761 in Paris	Military and civil engineer	Influential engineer who applied calculus to problems of artillery, hydraulics, and civil engineering
Bernoulli	Born: 8 Feb. 1700 in Groningen, Netherlands Died: 17 Mar. 1782 in Basel, Switzerland	Mathematician; physician	Co-developer of hydrodynamics; developed relationship between the velocity and pressure of fluids, known as the Bernoulli principle
Bernoulli	Born: 6 Jan. 1655 in Basel, Switzerland Died: 16 Aug. 1705 in Basel, Switzerland	Mathematician	Introduced the idea of polar coordinates and was one of the first to popularize calculus in Europe
Bernoulli	Born: 6 Aug. 1667 in Basel, Switzerland Died: 1 Jan. 1748 in Basel, Switzerland	Mathematician	Contributed greatly to the development of calculus and is considered one of the founders of the calculus of variations. Co-developer of hydrodynamics
Bignon	Born: 19 Sep. 1662 in Paris Died: 14 Mar. 1743 in Port-Royal, France	Abbot; librarian	Minister for academies, president and vice president of Academy of Sciences
Bonjean	Born: 16 Apr. 1778 in Paris Died: after January 1822	Constructor	Developed simplified curves of displacement and draft known as "Bonjean curves"

Borda	Jean Charles	Born: 4 May 1733 in Dax, France Died: 19 Feb. 1799 in Paris	Mathematician; physicist; administrator	Conducted extensive work in fluid resistance, measured an arc of the meridian to establish metric system. Instated standard system of construction. Head of French school of engineer-constructors of the navy
Bossut	Charles	Born: 11 Aug. 1730 in Tartaras, France Died: 14 Jan. 1814 in Paris	Mathematician; physicist	Wrote books on mathematics, fluids. Conducted ship resistance experiments
Bouguer	Pierre	Born: 16 Feb. 1698 in Le Croisic, France Died: 15 Aug. 1758 in Paris	Astronomer; hydrographer; mathematician	"Father of naval architecture"; wrote first work on the subject, <i>Traité du navire</i> . A leader of Academy of Sciences expedition to Peru to measure shape of the Earth. Developed laws for photometry and gravitational anomalies.
Bourde de Villehuet	Jacques-Pierre	Born: 1732 in Saint-Coulomb, France Died: 1789 in Lorient, France	Merchant ship officer	Wrote treatise on naval maneuvering and tactics
Burgues de Missessy-Quiès	Édouard Jacques, count of	Born: 1754 in France Died: 1829 in France	Naval officer	Admiral during Napoleonic Wars. Wrote a treatise on lading of ships
Camus	Charles Étienne Louis	Born: 25 Aug. 1699 in Crécy-en-Brie, France Died: 4 May 1768 in Paris	Mathematician; cartographer	Participated in Maupertuis's Lapland geodesic mission; later teacher at Duhamel du Monceau's "Little Navy School"
Castries	Charles Eugène Gabriel de La Croix, marquis of	Born: 5 Feb. 1727 in Paris Died: 1800 in Wolfenbützel, Germany	Statesman	Minister of the French navy. Reorganized the fleet during the Seven Years War.

Chapman	Fredrik Henrik (af)	Born: 9 Sep. 1721 in Gothenburg, Sweden Died: 19 Aug. 1808 in Karlskrona, Sweden	Constructor	Chief constructor of Swedish navy; popularized naval architecture theory
Choiseul	Étienne François, duke of	Born: 28 June 1719 in Lunéville, France Died: 8 May 1785 in Paris	Statesman	French minister of war and the navy. Sought to restore alliances with Spain and Austria; responsible for the expansion of French sovereignty. Authored 1765 ordinance that reorganized navy and army and instated ship theory in design
Clairaut	Alexis-Claude	Born: 7 May 1713 in Paris Died: 17 May 1765 in Paris	Mathematician; physicist; astronomer	Youngest member of French Academy of Sciences. Worked on geodesy, fluid mechanics
Clairin-Deslauriers	François Guillaume	Born: 1722 in France Died: 10 Oct. 1780 in Rochefort, France	Constructor	First student in Duhamel du Monceau's "Little School"; later chief constructor of French navy
Colbert	Jean Baptiste	Born: 29 Aug. 1619 in Reims, France Died: 3 Sep. 1683 in Paris	Statesman	Right-hand man of Louis XIV; minister of finance and the navy. Also founded the French Academy of Sciences and the Paris observatory
Condorcet	Marie-Jean-Antoine-Nicholas Caritat, marquis of	Born: 17 Sep. 1743 in Ribemont, France Died: 27 Mar. 1794 in Bourg-la-Reine, France	Mathematician; statesman	Developed theories of probability, worked on fluid resistance. Worked in Ministry of Finance; later a leader during the French Revolution
D'Alembert	Jean-Louis Le Rond	Born: 17 Nov. 1717 in Paris Died: 29 Oct. 1783 in Paris	Mathematician	Pioneered the study of partial differential equations. Author of major works on hydrodynamics. Co-editor with Diderot of <i>Encyclopédie</i>
Deane	Anthony	Born: 1638 in Harwich, Britain Died: 1721 in London	Constructor	Leading constructor of British navy; later surveyor general of the royal shipyards and commissioner of the navy

Du Buat	Pierre-Louis-Georges	Born: 23 Apr. 1734 in Tortisambert, France Died: 17 Oct. 1809 in Vieux-Condé, France	Engineer	Wrote major works on hydraulics
Duhamel (du) Monceau	Henri-Louis	Born: July 1700 in Paris Died: 22 Aug. 1782 in Paris	Botanist; administrator	Responsible for maintenance of naval timber. Inspector general of French navy; director of first school of naval architecture. Wrote first textbook on the subject
Duquesne	Abraham	Born: 1610 in Dieppe, France Died: 1 Feb. 1688 in Paris	Naval officer	Admiral of fleet during wars with Britain, Holland, Algiers, and Genoa
Elvius	Pehr	Born: 1710 in Sweden Died: 1749 in Sweden	Mathematician; administrator	Secretary of Swedish Academy of Sciences; wrote memoir on maneuvering
Euler	Leonhard	Born: 15 Apr. 1707 in Basel, Switzerland Died: 18 Sep. 1783 in St Petersburg, Russia	Mathematician	Most prolific mathematical writer of all time, publishing over 800 papers, including many works on rational mechanics
Fatio de Duillier	Nicolas	Born: 16 Feb. 1664 in Basel, Switzerland Died: 10 May 1735 in Madersfield, Britain	Mathematician	At center of calculus priority debate between Newton and Leibniz. Worked on masting, solid of least resistance
Fernández de Landa	José Romero	Born: 27 May 1735 in Galaroza, Spain Died: 5 Aug. 1805 in Madrid	Constructor	Chief constructor of Spanish navy; established new rules for shipbuilding
Fouchy	Jean-Paul Grandjean de	Born: 10 Mar. 1707 in Paris Died: 15 Apr. 1788 in Paris	Astronomer	Secretary of French Academy of Sciences
Gautier	Jean-François	Born: 14 May 1733 in Toulon, France Died: 15 Mar. 1800 in Paris	Constructor	Chief constructor for Spanish navy 1770–1782; director of French School for Engineer-Constructors of the Navy in 1800
Gay	Pierre de	Born: 1758 in France Died: 1819 in France	Constructor	Wrote numerous articles on shipbuilding and naval architecture in <i>Encyclopédie méthodique</i>

Gerner	Henrik	Born: 1742 in Denmark Died: 1787 in Denmark	Constructor	Chief constructor of Danish navy; translated Duhamel du Monceau's work
Godin	Louis	Born: 28 Feb. 1704 in Paris Died: 11 Sep. 1760 in Cadiz, Spain	Astronomer	Original leader of geodesic mission to Peru; later head of Navy Guards in Spain
Groignard	Antoine	Born: 4 Feb. 1727 in Solliés-Pont, France Died: 26 July 1799 in Paris	Constructor	Chief constructor of French navy; won several French Academy prizes
Hocquart	Jean-Hyacinthe	Born: 1650 in France Died: 17 Oct. 1723 in Paris	Administrator	Intendant of Toulon; proposed method of trapezoids to calculate ship volumes
Hoste	Paul	Born: 19 May 1652 in Pont-de-Veyle, France Died: 23 Feb. 1700 in Toulon, France	Mathematician; priest	Teacher of mathematics to Navy Guards; wrote treatises on naval tactics, naval architecture
Hudde	Johann van Waveren	Born: 23 Apr. 1628 in Amsterdam Died: 15 Apr. 1704 in Amsterdam	Mathematician	Developed ideas for maxima and minima before Newton and Leibniz invented calculus. Proposed method for admeasurement of ships
Huygens	Christiaan	Born: 14 Apr. 1629 in The Hague, Netherlands Died: 8 July 1695 in The Hague, Netherlands	Physicist; mathematician; astronomer	Invented pendulum clock. Developed principles concerning momentum, center of gravity, and centrifugal force. Engaged in long debate with Renau over maneuvering
Juan y Santacilia	Jorge	Born: 5 Jan. 1713 in Novelda, Spain Died: 21 July 1773 in Madrid	Naval officer; constructor; engineer; diplomat	Embarked on geodesic mission to Peru; later chief constructor in Spain and ambassador to Morocco. Wrote important work on ship theory
Judichær	Olaus	Born: 1661 in Denmark Died: 1729 in Denmark	Mathematician; constructor	Chief constructor of Danish navy; developed displacement calculations
La Condamine	Charles Marie de	Born: 28 Jan. 1701 in Paris Died: 4 Feb. 1774 in Paris	Explorer; scientist	Embarked on geodesic mission to Peru; descended Amazon. Wrote about his exploits

La Croix	César-Marie de	Born: 1690 in France Died: 11 Jan. 1747 in Paris	Administrator	Commissioner of Toulon, Rochefort, Martinique. Wrote papers on longitude, ship stability
Lavanha	João Baptista	Born: 1550 in Portugal Died: 31 Mar. 1624 in Madrid	Mathematician; engineer	Chief engineer and cosmographer to Phillip II of Spain; was first to use term "naval architecture"
Le Monnier	Pierre Charles	Born: 20 Nov. 1715 in Paris Died: 3 Apr. 1799 in Herills, France	Astronomer	Embarked on geodesic mission to Lapland
Maffioletti	Gianmaria	Born: 1738 in Venice Died: 25 Jan. 1802 in Venice	Architect; priest	Formed Venice School of Naval Architecture
Mairan	Jean Jacques d'Ortous de	Born: 26 Nov. 1678 in Béziers, France Died: 20 Feb. 1771 in Paris	Physicist; mathematician	Observed the motion of pendulums in relation to the shape of the Earth. Director of the French Academy of Sciences
Maitz de Goimpy	François Louis Edme Gabriel, count of	Born: 10 Apr. 1729 in St Léger des Aubées, France Died: 29 Dec. 1807 in Billancourt, France	Constructor	Wrote treatise on construction of ships
Marguerie	Jean-Jacques de	Born: 1742 in Mondeville, France Died: 1779 off island of Grenada	Naval officer	Wrote several treatises on ship theory
Mariotte	Edmé	Born: 1620 in Dijon, France Died: 12 May 1684 in Paris	Physicist	Investigated the motion of pendulums; studied laws of fluid resistance and hydrostatics
Maupertuis	Pierre Louis Moreau de	Born: 28 Sep. 1698 in Saint Malo, France Died: 27 July 1759 in Basel, Switzerland	Astronomer	Embarked on geodesic mission to Lapland; later president of Berlin Academy of Sciences
Maurepas	Jean-Frédéric Philippe Phélypeaux, count of	Born: 9 July 1701 in Versailles, France Died: 21 Nov. 1781 in Versailles, France	Statesman	French minister of navy and chief adviser of Louis XVI. Supporter of applying science to questions of navigation and ship construction

Newton	Isaac	Born: 25 Dec. 1642 in Woolsthorp, Britain Died: 20 Mar. 1727 in London	Mathematician; physicist; alchemist	By far the greatest contributor to development of modern science. Inventor of calculus. Published <i>Principia</i> , which contained his three fundamental laws of motion
Ollivier	Blaise	Born: 1701 in Toulon, France Died: 20 Oct. 1746 in Brest, France	Constructor	Wrote about shipbuilding in Britain and Netherlands; first calculations of ship weight
Pardies	Ignace Gaston	Born: 5 Sep. 1636 in Pau, France Died: 21 Apr. 1673 in Paris	Priest; mathematician	Wrote fundamental text on mechanics
Parent	Antoine	Born: 16 Sep. 1666 in Paris Died: 26 Sep. 1716 in Paris	Mathematician	Worked on analytic geometry
Petty	William	Born: 26 May 1623 in Romsey, Britain Died: 16 Dec. 1687 in London	Economist; cartographer	First known writer on economics with conclusions supported by statistical data. Developed and built catamaran vessels
Pitot	Henri de	Born: 3 May 1695 in Aramon, France Died: 27 Dec. 1771 in Aramon, France	Civil engineer	Wrote treatise on ship maneuvering; studied fluid pressures
Poleni	Giovanni	Born: 23 Aug. 1683 in Venice Died: 15 Nov. 1761 in Padua, Italy	Mathematician; astronomer; engineer	Worked on canal and river systems in northern Italy. Consulted with Venice navy on ship projects
Polhem (Polhammer)	Christoph	Born: 18 Dec. 1661 in Visby, Sweden Died: 30 Aug. 1751 in Sweden	Engineer	Developed hydraulic-powered factories. Wrote memoir on stability of ships
Renau d'Elizagaray	Bernard	Born: 2 Feb. 1652 in Armendaritz, France Died: 30 Sep. 1719 in Pougues, France	Military engineer; constructor	Developed theory of ships based on ellipses; later wrote on ship maneuvering. Invented mortar ship

Richelieu	Armand-Jean du Plessis, duke of	Born: 5 Sep. 1585 in Paris Died: 4 Dec. 1642 in Paris	Cardinal; statesman	Political spokesman for the Catholic Church until being named secretary of state under King Louis XIII. Held enormous political sway in fighting for the unification of France. Pioneered initial reconstruction of French navy
Robins	Benjamin	Born: 1707 in Bath, Britain Died: 20 July 1751 in Madras, India	Mathematician; military engineer	Wrote on laws of motion and impacts of rigid bodies. Experiments led to improvements in gunnery and fortifications
Romme	Nicolas Charles	Born: 8 Dec. 1745 in Riom, France Died: 14 Mar. 1805 in Rochefort, France	Mathematician	Wrote books on masting and naval architecture, conducted experiments on stability and resistance
Roquefeuil-Kerlouet	Aymar-Joseph, count of	Born: 19 Mar. 1714 in Brest, France Died: 1824 in France	Naval officer	Fought during Seven Years War. Founder of French Academy of Navy; gave strong support to scientific investigations in naval architecture
Saveur	Joseph	Born: 24 Mar. 1653 in La Flèche, France Died: 9 July 1716 in Paris	Military engineer; mathematician	Worked under Vauban on fortifications. Wrote treatises on music, fluid resistance. Edited Renau's work on maneuvering
Savérien	Alexandre	Born: 1720 in Arles, France Died: 1805 in France	Constructor; philosopher	Wrote works on maneuvering and navigation, as well as nautical dictionary and works on philosophy
Seignelay	Jean-Baptiste Colbert, marquis of	Born: 1 Nov. 1651 in Paris Died: 3 Nov. 1690 in Versailles, France	Statesman	Eldest son of Jean-Baptiste Colbert; became minister of navy
Sheldon	Francis (II)	Born: 26 June 1755 in Karlskrona, Sweden Died: 7 May 1817 in Stockholm, Sweden	Constructor	Son of Gilbert Sheldon, contemporary of Fredrik Henrik af Chapman; led Fleet Constructors Corps

Sheldon	Gilbert	Born: 21 Jan. 1710 in Karlskrona, Sweden Died: 20 Apr. 1794 in Karlskrona, Sweden	Constructor	Son of Francis Sheldon, British constructor who came to Sweden. Became chief constructor to Swedish navy
Smeaton	John	Born: 8 June 1724 in Austhorpe, Britain Died: 28 Oct. 1792 in Austhorpe, Britain	Engineer	Conducted numerous experiments in hydraulics and resistance
Stevin	Simon	Born: 1548 in Bruges, Belgium Died: Mar. 1620 in The Hague, Netherlands	Engineer	Built forts and dikes, taught engineering. Made important contributions to hydrostatics, geography, fortifications, and navigation.
Stibolt	Ernst Vilhelm	Born: 14 Feb. 1742 in Christiansö, Denmark Died: 29 Feb. 1796 in Copenhagen	Constructor	Wrote treatise on strength of ships
Stratik (Stratico)	Šimun Filin (Simone)	Born: 1733 in Zara, Croatia Died: 1824 in Italy	Architect; engineer	Professor in Padua; taught at Venice School of Naval Architecture; translated several works of ship theory
Thévenard	Antoine-Jean Marie	Born: 7 Dec. 1733 in Saint Malo, France Died: 9 Feb. 1815 in Paris	Merchant and naval officer	Commodore of the East Indies Company prior to joining the French navy. Conducted important experiments on ship resistance
Tourville	Anne-Hilarion de Cotentin, count of	Born: Nov. 1642 in Tourville, France Died: 23 May 1701 in Paris	Naval officer	Admiral in the French navy during war against Britain. Supported development of scientific theories of construction
Turgot	Anne-Robert-Jacques	Born: 10 May 1727 in Paris Died: 20 Mar. 1781 in Paris	Scientist; statesman	Controller general of finances under Louis XVI; implemented new economic principles such as free trade and income tax

Ulloa y de Torre-Guiral	Antonio de	Born: 12 Jan. 1716 in Seville, Spain Died: 5 July 1795 near Cadiz, Spain	Naval officer; naturalist; diplomat	Embarked on geodesic mission to Peru; later governor in Spanish Louisiana. Credited with discovery of platinum
Varignon	Pierre	Born: 1654 in Caen, France Died: 23 Dec. 1722 in Paris	Mathematician	Contributed to graphical statics, mechanics, application of differential calculus
Vauban	Sébastien Le Prestre, marshal of	Born: 1 May 1633 in Saint-Léger-de-Foucheret, France Died: 30 Mar. 1707 in Paris	Military engineer	Developed system of fortifications, siege warfare. Supporter of Renau
Vial du Clairbois	Honoré-Sébastien	Born: 27 Mar. 1733 in Paris Died: 20 Dec. 1816 in Brest, France	Constructor	Wrote textbooks and articles on naval architecture; director of French School for Engineer-Constructors of the Navy 1800–1810
Wallis	John	Born: 23 Nov. 1616 in Ashford, Britain Died: 28 Oct. 1703 in Oxford	Mathematician	Introduced infinite series and infinite products. Developed mathematical ship form
Witsen	Nicolaes	Born: 8 May 1641 in Amsterdam Died: 6 Aug. 1717 in Amsterdam	Statesman; explorer	Mayor of Amsterdam; expert on Dutch shipbuilding; made maps of Russia.
Zwijndregt	Pieter Pauluszoon van	Born: 1711 in the Netherlands Died: 1790 in the Netherlands	Constructor	Chief constructor in Rotterdam dockyard. Conducted model tests for optimum hull form

Notes

Preface

1. This reference is from Owen and Niedermair, “Geometry of the Ship,” in *Principles of Naval Architecture*, (1947) p. 48; also in rev. 1st ed. (1967), p. 38, and 2nd ed. (1988), p. 45.

2. Bonjean, *Nouvelles échelles de déplacement* (1810).

3. Bonjean, “Etat de service” (1822).

4. Ferreiro, “Down from the Mountain” (2004). I thank Alistair Greig, University College London, and David Edgerton at Imperial College London for inspiring me to pursue this curriculum, and Robert Iliffe at Imperial College London for his guidance during it.

5. See for example, books by Jean Boudriot, especially *Le Vaisseau de 74 canons* (1973–1975/1986–1988); Conway’s History of the Ship series, such as Brown, *Before the Ironclad* (1990); books by Norman Friedman such as *U.S. Destroyers* (1982); and works such as Griffiths, Andrews, and Walker, *Brunel’s Ships* (1999). The work in marine archaeology is also vast, but has tended to concentrate on specific details of wooden ship and boat geometry and construction. This is changing as marine archaeologists are now studying how naval architecture impacts ship and boat construction, e.g., Castro, *Ship Treatises Project*, accessed December 2003.

6. Vincenti, *What Engineers Know and How They Know It* (1990); Rouse and Ince, *History of Hydraulics* (1957).

7. Hall, *The Scientific Revolution 1500–1800* (1954/1962), p. xii. In a subsequent work, *The Revolution in Science 1500–1750*, 3rd ed. (1983), p. vii, Hall redefines the age as ending in the middle of the eighteenth century. But for my purposes, Hall’s earlier definition is most appropriate as it does not interrupt the flow of ideas, begun by Newton and his contemporaries in the 1600s, that were consolidated by Euler and others during the mid-to-late 1700s.

8. I thank the naval historian Jakob Seerup for this insight.

9. Wooley, “On the Present State of the Mathematical Theory of Naval Architecture” (1860). Wooley took the name “Juan d’Ulloa” from a clumsy 1851 translation of a book by Juan y Santacilia and Ulloa on the Geodesic Mission to Peru.

10. Juan y Santacilia, *Exámen marítimo* (1771), vol. 1, pp. v–xxx.
11. Duhamel du Monceau, *Éléments de l'architecture navale* (1752), German translation by Müller (1791/1973), pp. ii–xlvi.
12. Montucla, *Histoire des mathématiques* (1802/1968), book 4, pp. 381–504.
13. Charnock, *A History of Marine Architecture* (1800–1802).
14. Fincham, *A History of Naval Architecture* (1851/1979), pp. ix–lxxxiv.
15. Pollard and Dubebout, *Architecture navale: Théorie du navire*, vol. 1 (1890), pp. vii–liv.
16. Two examples are Gilfillian, *Inventing the Ship* (1935); and Abell, *The Shipwright's Trade* (1948/1962).
17. Stoot, “Some Aspects of Naval Architecture in the Eighteenth Century” (1958), and “Ideas and Personalities in the Development of Naval Architecture Century” (1958). At the end of the first paper (p. 41), delivered in Paris on 2 July 1958, Stoot expressed the hope that some competent authority will produce such a work [an authoritative account of the development of naval architecture] in the not too distant future.” I have remarked to Fred Stoot that he said those words only three weeks after I was born, and that I very much hope to become that “competent authority” he was looking for.
18. Timmermann, *Die Suche nach der günstigsten Schiffsform* (1979).
19. Hall, “Architectura Navalis” (1979–1980).
20. See, for example, the Max Planck Institute for the History of Science, History of shipbuilding and ship design Web site, accessed January 2004.
21. RINA Web site, accessed January 2004.
22. An English-language translation of Lavanha is available on the Richard Barker Web site, accessed December 2003.
23. Furttenbach, *Architectura Navalis* (1629/1975). I thank the professional translator Andrew Fenner for assisting me in interpreting this work.
24. Digges, *Stratiticos* (1579), n.p.; Dudley, *Dell'arcano del mare* (1646/1661), book 4, p. 3; Dassié, *L'Architecture navale* (1677/1695/1994), p. ii.
25. Vial du Clairbois, *Essai géométrique et pratique sur l'architecture navale* (1776).
26. Fincham, *A History of Naval Architecture* (1851/1979), pp. v–viii.
27. Pollard and Dubebout, *Architecture navale*, vol. 1 (1890), pp. v–vi.
28. Two examples are Kline, “Construing ‘Technology’ as ‘Applied Science’” (1995); and Oldenziel, *Making Technology Masculine* (1999), pp. 23–51.
29. Lamb, *Ship Design and Construction* (2003); Lewis, *Principles of Naval Architecture* (1988).

30. Lewis, *Principles of Naval Architecture*, vol. 1 (1988), pp. 304–306.

31. I principally used the online inflation calculator on the Economic History Services Web site, *How Much Is That?*, accessed June 2003, to calculate modern values in pounds sterling. For the exchange rate between *livre tournois* and the pound, I refer to Parker, *The Thirty Years' War* (1997), p. xviii, for 1648; for 1750 I gratefully acknowledge the help of the Federal Reserve Bank of Chicago economist François Velde, who interpreted the London Course of the Exchange weekly data for me. I referred to OECD, *Main Economic Indicators* (2004), p. 24, to convert modern pounds to dollars at the purchasing-power-parity rate.

Prologue: Down from the Mountain

1. Robbs, “Presidential Address” (1954), p. 4.

2. See Bouguer: *Optical Treatise on the Gradation of Light* (1961), pp. v–xiv, for a short history of this field.

3. Lamontagne, *La Vie et l'oeuvre de Pierre Bouguer* (1964). In 1998 Lamontagne printed (in a limited edition) a collection of notes and essays titled *Pierre Bouguer, 1698–1758: Un Blaise Pascal du XVIII^e siècle*. I thank him for providing me a copy of this work, as well as for a steady stream of correspondence on Bouguer.

4. Chesnais, “Les Trois Bouguer et Le Croisic” (2002), pp. 9–13.

5. Jean Bouguer, *Traité complet de la navigation* (1698/1706); Fauque, “Les Écoles d’hydrographie en Bretagne au XVIII^e siècle” (2000), p. 382; Chesnais, “Les Trois Bouguer et Le Croisic” (2002), pp. 18–19. The house conforms to the property description of the purchase by Jean Bouguer in 1711, and it has a “1712” inscription conforming to the known date of enlargement, but no records have yet been found firmly establishing the house as his. However, it should be noted that the street next to the house (on the right in figure P.2) was renamed “rue Pierre Bouguer” in the 1800s, most probably because the local historians had learned from their ancestors that Bouguer lived in that house. Bouguer dedicated his 1734 *Entretien sur la cause d’inclinaison des orbites des planètes* (Discussion on the Cause of the Inclination of the Orbits of Planets) to his “friend Paul Desforges Maillard.” Desforges Maillard’s encounters with Voltaire would be immortalized in 1878 by the British poet Robert Browning in “Two Poets of Croisic.” I thank René and Ghislaine Chesnais for this wealth of information, and especially for showing me the wonderful little town of Le Croisic.

6. Grandjean de Fouchy, “Éloge de M. Bouguer” (1758), pp. 127–128; Fauque: “Du Bon Usage de l’éloge: Cas de celui de Pierre Bouguer” (2001), pp. 355–356. I am grateful to Danielle Fauque for additional information on Bouguer and his era.

7. Grandjean de Fouchy, “Éloge de M. Bouguer” (1758), pp. 128–129; Fauque: “Du Bon Usage de l’éloge: Cas de celui de Pierre Bouguer” (2001), pp. 357–363.

8. Bouguer, letter to Maurepas (1729).

9. Ibid.; Bouguer, letter to Maurepas (1730); Bouguer, letter to Bignon (1733); Chesnais, “Les Trois Bouguer et Le Croisic” (2002), pp. 14, 20.
10. Bouguer’s introduction to Reyneau and the Academy of Sciences is discussed in Fauque, “Du Bon Usage de l’éloge: Cas de celui de Pierre Bouguer” (2001), pp. 364–372.
11. Bouguer, letter to Maurepas (1726); Bouguer, letter to Bignon (1733).
12. Bouguer, letter to Maurepas (1730).
13. Anthiaume, Pierre Bouguer (1698–1758) (1914), p. 139; Lamontagne, *Pierre Bouguer, 1698–1758: Un Blaise Pascal du XVIII^e siècle* (1998), p. 26; Bouguer, *Optical Treatise on the Gradation of Light* (1961), p. vi. I thank the science historian Danielle Fauque for additional information.
14. Anthiaume, “Pierre Bouguer (1698–1758)” (1914), p. 139; Maheu, “Bibliographie de Pierre Bouguer (1698–1758)” (1966), pp. 194–195.
15. Bouguer, letter to Bignon (1733).
16. Demerliac, *La Marine de Louis XVI: Nomenclature des navires français de 1715 à 1774* (1995), p. 68.
17. Bouguer, letter to Maurepas (January 1734).
18. See Smith, *From Plane to Spheroid* (1986), for an in-depth description of the evolution of the science and techniques of geodesy.
19. Much of the information in the following section comes from the two most thorough sources I have found regarding the Geodesic Mission: Erickson, “The French Academy of Sciences Expedition to Spanish America, 1735–1744” (1955), a Ph.D. dissertation which, in my opinion, is long overdue for publication; and Lafuente and Mazuecos, *Los caballeros del Punto Fijo* (1987). Among their other attributes, they provide thorough citations for the numerous primary source documents regarding the geodesic mission, which I do not repeat here but which I have consulted.
20. Grandjean de Fouchy, “Éloge de M. Bouguer” (1758), p. 131.
21. Bouguer, “Comparaison des deux loix” (1734). A thorough explanation of the relevance of this paper to geodesy is given in Greenberg, *The Problem of Earth’s Shape from Newton to Clairaut* (1995), pp. 89–106.
22. Bouguer, letter to Maurepas (November 1734).
23. Bignon, letter to Bouguer (18 December 1734); Bignon, letter to Maurepas (26 December 1734); Bignon, letter to Maurepas (29 December 1734); Fauque, “Du Bon Usage de l’éloge: Cas de celui de Pierre Bouguer” (2001), pp. 355–356. I suspect that Bignon’s claim that he suggested Bouguer for the expedition was a ruse, and that Maurepas had Bouguer in mind all along.
24. Demerliac, *La Marine de Louis XVI: Nomenclature des navires français de 1715 à 1774* (1995), p. 78.

25. Voltaire, *Alzire; ou les Américains* (1736).

26. For a critical evaluation of Maupertuis's expedition, see Iliffe, "'Aplatisseur du monde et de Cassini'"; Maupertuis, "Precision Measurement and the Shape of the Earth in the 1730s" (1993).

27. The historical novels *Le Procès des étoiles* (The Trial of the Stars) by Florence Trystram (1979) and *Le Corps du monde* (The Body of the World) by Patrick Drevet (1997), although fictional accounts, are largely based on thorough research, and provide the most readable accounts of the human side of the Geodesic Mission. I am grateful to both authors for providing me with insights into their methods of work.

28. See Smith, *From Plane to Spheroid* (1986), for an in-depth description of this process. I thank James Smith for his further explanations.

29. In January 2005 construction of a new international airport that will eventually cover the Geodesic Mission's baseline began at Yaruquí (Caraburo).

30. I thank Nelson Gómez for his tour of the area of the baseline at Yaruquí and for his thorough explanations of the expedition, in particular the role of the indigenous peoples in its ultimate success.

31. Jaguars, actually. The quote is from Lamontagne, *La Vie et l'oeuvre de Pierre Bouguer* (1964), p. 82.

32. The currently accepted value is 110,568 meters; the work of the geodesic mission was astonishingly accurate for its day. A complete analysis of the results is given in Smith, *From Plane to Spheroid* (1986).

33. Bouguer, *Traité du navire* (1746), p. v.

34. Bouguer, biographical dossier, not indexed; letter from Bouguer to Réaumur (1738).

35. Bouguer, *Traité du navire* (1746), p. xxiv.

36. Ibid.; Bouguer noted in the preface: "the Book being entirely finished: now four or five years ago, as I write now in France." Bouguer most likely wrote his preface in mid-to-late 1745, soon after the Academy of Sciences approved the book for publication on 15 May (ibid., "Privilège du roi" page), and before its publication in 1746. This would put the approximate date of completion as 1740/1741, after the survey was essentially completed and he was in Quito for long stretches.

37. Juan y Santacilia, *Exámen marítimo, Theórico Práctico* (1771/1992).

38. Bouguer, *Traité du navire* (1746), p. xxiv. I speculate that this "reputable person" was a Jesuit, given Bouguer's Jesuit training and the excellent relations that he had with the order. However, when the Jesuits were expelled from Peru in 1769, many of their books and manuscripts were lost, and it is likely that Bouguer's duplicate manuscript was lost as well. An exhaustive search of archives, museums, and libraries in Ecuador, Peru, Columbia, Spain, France, and Italy has so far not turned up this second manuscript, although it may be unmarked or under another name

and awaiting a chance discovery. Finding this copy of the original manuscript of *Traité du navire* would be a major discovery, as it would allow comparison with the published book to see what Bouguer had changed during his voyage home.

39. Cros, “Verguin, un ingénieur bâtisseur” (2001).

40. Jussieu’s story is fictionalized in Drevet, *Le Corps du monde* (1997).

41. Recent translations of these works are Juan y Santacilia and Ulloa, *A Voyage to South America* (1964); Juan y Santacilia and Ulloa, *Discourse and Political Reflections on the Kingdoms of Peru* (1978).

42. Some of Godin’s later story is told in Lafuente and Sellés, *El observatorio de Cadiz (1753–1831)* (1988).

43. See McConnell, “La Condamine’s Scientific Journey Down the River Amazon” (1991), for a critical examination of the voyage.

44. Isabel Godin’s remarkable story is best retold in Whitaker, *The Mapmaker’s Wife* (2004).

45. Some of the influence of the geodesic mission, and of the voyage of Humboldt to South America, is discussed in Appel, *Francisco José de Caldas: A Scientist at Work in Nueva Granada* (1994).

46. Bouguer stated in *Traité du navire* (1746), p. 322: “I have numerous times remarked, on returning on *the Triton*, little ship of Nantes of about 180 tuns, that each oscillation [of roll] was a little more than 4-1/2 seconds.” Identification of the ship is from Bouguer, certification of Pierre Fouré (1744); and Anonymous “Rôle de désarmement du *Triton*” (1744). I am grateful to Jean-François Caraës for his assistance. The particulars of *Triton*’s voyage are given in Mettas, *Répertoire des expéditions négrières françaises au XVIII^e siècle*, vol. 1 (1978), pp. 276–277.

Chapter 1: “Mere Carpenters”

1. Juan y Santacilia, *Examen marítimo* (1771), vol. 1, p. v.

2. Lévêque was particularly condescending to British constructors; in his letter to Minister of the Navy Antoine Raymond de Sartine, recommending the translation of *Examen marítimo* he argued, “None of the nations of Europe have toiled as much in this grand art as the French, and our superiority at all levels is solidly established. Even the English cannot contest this, as they build and continue to build their vessels according to simple laws furnished by experience, without having first been enlightened by a luminous Theory; they have always copied us fervently, and have meticulously preserved the Lines of our vessels which have fallen into their hands; they do not have even one theoretical work on this important branch.” Lévêque, letter to Sartine (1779).

3. Fincham, *A History of Naval Architecture* (1851/1979), p. x.

4. Holmes, *Ancient and Modern Ships* (1906), p. 56; Hoving and Lemmers, *In tekening gebracht* (2001), p. 78.

5. Gardiner, *The Heavy Frigate* (1994), pp. 40–42, 118.

6. Forfait, *Traité élémentaire de la mâture des vaisseaux* (1788), p. i.
7. Keegan, *The Price of Admiralty* (1988), p. 47. Naval cannon were larger and fired heavier shot than army cannon.
8. Quoted in Juan-García Aguado, *José Romero Fernández de Landa* (1998), pp. 110–111. The letter is also discussed in chapters 3 and 4.
9. The naval historian Jan Glete also makes this argument that theory was a power tool for the state more than a means for optimization (Glete, *Navies and Nations* [1993], Volume 1, pp. 48–51). I extend my thanks to him for sending me additional, unpublished material of his that reinforces this crucial concept.
10. Friedman, *Seapower as Strategy* (2001), pp. 14–15.
11. McNeill, *Atlantic Empires of France and Spain* (1985), pp. 74–79.
12. See Glete, *Navies and Nations* (1993), for a detailed explanation of the source data. Among many other works, see Harding, *Seapower and Naval Warfare, 1650–1830* (1999), for a more focused analysis, principally concerning the British/French conflicts.
13. An overview of European trading companies is given in Blussé and Gaastra, *Companies and Trade* (1981). For a full description of the French East Indies Company, see Haudrère, *La Compagnie Française des Indes au XVIII^e siècle* (1989); and Beauchesne, *Historique de la construction navale à Lorient de 1666 à 1770* (1980). The statement about Colbert and Dutch warehouses is from Murat, *Colbert* (1980/1984), p. 143.
14. Klein, “Origins of Trading Companies” (1981), p. 23.
15. Wikipedia online encyclopedia, Article on VOC, accessed December 2003.
16. Hoving and Lemmers, *In tekening gebracht* (2001), pp. 98, 111.
17. Sutton, *Lords of the East* (1981), pp. 37–52.
18. Joint Doctrine Division, *Department of Defense Dictionary of Military and Associated Terms* (2003).
19. The relationship among science, technology, and operations is also explored in Glete, *Navies and Nations* (1993), pp. 19–21, and Rodger, *Command of the Ocean* (2005), pp. 408–425.
20. The impact of guns at sea is discussed in Parker, *The Military Revolution* (1988/1996), pp. 82–114.
21. For an overview of line of battle doctrine, see Tunstall and Tracy, *Naval Warfare in the Age of Sail: The Evolution of Fighting Tactics 1650–1815* (1990).
22. The role of standardization is discussed in Glete, *Navies and Nations* (1993), pp. 43–48.
23. Llinares, *Marine, propulsion et technique* (1994), is a comprehensive and very readable analysis of sailing rig standardization in the French navy.

24. Gawronski et al., *Hollandia Compendium* (1992), pp. 34–46; Llinares, “La Flotte de la Compagnie Française des Indes au XVIII^e siècle: Une Normalisation inachevée” (1996).
25. The Borda–Sané standardization is discussed in Villiers, *Marine royale, corsaires et trafic* (1991), pp. 701–704; and Boudriot, *Les Vaisseaux de 74 à 120 canons* (1995), pp. 158–195.
26. Harding, *Seapower and Naval Warfare* (1999), p. 231.
27. Gardiner, *The First Frigates* (1992), pp. 107–109.
28. The role of timber in the construction of ships is a vast area of study that continues to be critically examined. Its importance is underlined by the fact that national timber supplies were often under the purview of the navy, with constructors put in charge of forest management. Among the many works on this subject, the two classic texts are Albion, *Forests and Sea Power: The Timber Problem of the Royal Navy, 1652–1862* (1926/1999), and Bamford, *Forests and French Sea Power, 1660–1789* (1956).
29. Knight, “The Introduction of Copper Sheathing into the Royal Navy” (1973); Harris, “Copper and Shipping in the Eighteenth Century” (1966/1992); Boudriot, *The History of the French Frigate* (1993), pp. 150–153.
30. In all industries today, not just maritime ones, paper plans are largely being replaced by three-dimensional computer models, leading a noted professor of naval architecture, Horst Nowacki, to quip that paper plans represented a 500-year detour in the development of solid modeling.
31. Deng, *Maritime Sector, Institutions and Sea Power of Premodern China* (1999), p. 18. I thank Gang Deng for providing additional information on this subject.
32. For an excellent overview of these and other ship models, see Franklin, *Navy Board Ship Models, 1650–1750* (1989); and Lavery and Stephens, *Ship Models: Their Purpose and Development from 1650 to the Present* (1995).
33. On the British constructors in Sweden, see Svensson, “Skeppsbyggeriet” (1963); and for those in Denmark, see Harris, “Francis Sheldon in Denmark 1686–1690” (1997). The development of Dutch maritime models of all types is described in considerable detail in Lemmers, *Techniek op schaal* (1996).
34. Franklin, *Navy Board Ship Models 1650–1750* (1989), p. 2.
35. The use of “lift” half-models, in which a half-hull model (i.e., showing only the port or sometimes starboard half of the hull) was formed of pegged-together planks which could be lifted apart to trace lines, is briefly described in Chapelle, *The Search for Speed Under Sail* (1967), pp. 150–151.
36. I thank the maritime historian Ab Hoving for his insights into the use of ship models.
37. A comprehensive discussion of the derivation, use, and misuse of the term “whole-moulding” is found in Barker, “Whole-Moulding: A Preliminary Study of Early English and Other Sources” (2003).

38. Many dozens of books and articles have been written about design and control methods for wooden ships. Some worth noting are Barker, “‘Many May Peruse Us’: Ribbands, Moulds and Models in the Dockyards” (1988); Reinders and Paul, *Carvel Construction Technique: Skeleton-First, Shell-First* (1991); Rieth, *Le Maître-gabarit, la tablette et le trebuchet* (1996), and *Concevoir et construire les navires* (1998); Nowacki and Valleriani, *Shipbuilding Practice and Ship Design Methods from the Renaissance to the 18th Century* (2003).

39. See Barker, “Fragments from the Pepysian Library” (1986), for a description of Baker’s treatise.

40. Manera Regueyra, *El buque en la Armada Española* (1981/1999), pp. 172–173; Fernández González: “Arquología de la arquitectura naval” (1996), p. 218; Penzo, *Navi veneziane/Venetian Ships* (2000), pp. 36–37.

41. Erlande-Brandenburg and Vich, *Catalogue des plans des bâtiments à voiles* (1996), p. xi.

42. Of the many, many texts that describe the graphical design techniques used by naval constructors in the 1700s, one of the clearest and most visually impressive is Hoving and Lemmers, *In tekening gebracht* (2001). Monge’s *Géométrie descriptive* (Descriptive Geometry), widely published only in 1811, was the first work to develop the basic theory of accurately depicting complex solid objects in two dimensions, and is considered the foundation for modern engineering drawings. A concise description is given in Booker, “Gaspard Monge (1756–1818) and His Effect on Engineering Drawing and Technical Education” (1961), and in his *A History of Engineering Drawing* (1963/1979), pp. 86–113.

43. See Nowacki, “Splines im Schiffbau” (2000), for a synopsis of this development.

44. Johnston, “Making Mathematical Practice” (1994), pp. 137–165; Barker, “English Shipbuilding in the Sixteenth Century” (1998), pp. 120–122.

45. A project to provide online descriptions of major shipbuilding treatises has been started at Texas A&M University by Filipe Vieira de Castro. Castro, Ship Treatises Project, accessed December 2003.

46. My thanks to the technology historian David McGee, who as of July 2005 was participating in a project to transcribe and publish the manuscript of Michael of Rhodes.

47. Dotson, “Treatises on Shipbuilding Before 1650” (1994), pp. 162–166.

48. An English-language translation is available as García de Palacio, *Nautical Instruction 1587* (1986).

49. Dotson, “Treatises on Shipbuilding Before 1650” (1994), pp. 165–166.

50. Alberti and Fausto are discussed in Concina, “Humanism on the Sea” (1988), and in his *Navis: L’umanesimo su mare* (1990), pp. 71–99.

51. Johnston, *Making Mathematical Practice* (1994), p. 162.

52. An English-language translation of Lavanha is available on the Richard Barker Web site, accessed December 2003.

53. Furttenbach, *Architectura Navalis* (1629/1975). I thank the professional translator Andrew Fenner for his explanation of the work.
54. Fournier, *Hydrographie* (1643/1667/1973).
55. Witsen, *Aeloude en hedendaegsche scheeps-bouw en bestier* (1671/1979). For a clear explanation and context of Witsen's work, see the reprint with commentary in Hoving, *Nicolaes Witsens Scheeps-bouw-konst open gestelt* (1994).
56. Deane, *Deane's Doctrine of Naval Architecture* (1670/1981).
57. Dassié, *L'Architecture navale* (1677/1695/1994).
58. Rålamb, *Skeps byggerij* (1691/1943). This work is briefly discussed in Svensson, "Skeppsbyggeriet" (1963).
59. Novi, "The Marqués de la Victoria and the Advancement of Naval Lexicography in Eighteenth-Century Spain" (1997).
60. These treatises are discussed in Hoving and Lemmers, *In tekening gebracht* (2001), pp. 80–83, 111–125.
61. Lamb, *Ship Design and Construction* (2003); Lewis, *Principles of Naval Architecture* (1988).

Chapter 2: Deriving the *Dérive*

1. See O'Malley, *The First Jesuits* (1993), for details of this early period.
2. See Dainville, "L'Enseignement scientifique dans les collèges des Jésuites" (1964); Hahn, "L'Enseignement scientifique des Gardes de la Marine au XVIII^e siècle" (1964); Martin, *The Jesuit Mind* (1988); Feldhay, "The Cultural Field of Jesuit Science" (1999); Feingold, "Jesuits: Savants" (2003).
3. This critical feature of Jesuit management is described in Harris, "Mapping Jesuit Science" (1999).
4. See Baldwin, "Pious Ambition" (2003).
5. A more detailed examination of the Lisbon earthquake and Pombal's expulsion of the Jesuits is given in Leidner, *The Lisbon Earthquake of 1755*, accessed April 2003.
6. See Morgan, *Histoire du Journal des sçavans* (1929).
7. Several works that cover these journals are Kronick, *A History of Scientific and Technical Periodicals* (1976); Laeven, *The "Acta Eruditorum" Under the Editorship of Otto Mencke* (1990), and *Scientific and Technical Periodicals of the Seventeenth and Eighteenth Centuries* (1991); and Taton, "Le Rôle et l'importance des correspondances scientifiques aux XVII^e et XVIII^e siècles" (2000).
8. See Barber, "Who Were the Booksellers of the Enlightenment?" (1981); Chartier and Martin, *Histoire de l'édition française*, vol. 2, *Le Livre triomphant 1660–1830* (1990); and Darnton, *The Business of Enlightenment* (1997). I thank the publishing historian Catherine Bousquet-Bressolier for providing pricing information.

9. Truesdell, “Editor’s Introduction” (1955), p. x. At the time, Euler was a member of the Berlin Academy of Sciences, which did not have its own in-house publisher.
10. See Marker, *Publishing, Printing and the Origins of Intellectual Life in Russia* (1985), for a general discussion.
11. Many Paris booksellers, including Guerin and Michallet, were clustered near the Sorbonne. Jombert was on rue Saint Jacques (the site is now occupied by a camping supply store) before it moved to Quai des Augustins, across the river from the Louvre, where the Academy of Sciences met.
12. Bousquet-Bressolier, “Charles-Antoine Jombert” (1997); Parent-Charon, *Quel Publique pour le livre maritime?* (2005). My thanks to Annie Parent-Charon for providing me an advance copy of her paper.
13. See Ornstein: *The Rôle of Scientific Societies in the Seventeenth Century* (1928/1975); Brown, *Scientific Organizations in Seventeenth Century France* (1934/1967); and Cardwell, *The Organisation of Science in England* (1957/1972); and Merton, *Science, Technology and Society in Seventeenth Century England* (1970).
14. See Brown, *Scientific Organizations in Seventeenth Century France* (1934/1967); and Cardwell, *The Organisation of Science in England* (1957/1972).
15. See Neuville, “Les Établissements scientifiques de l’ancienne marine” (1878, 1879), for a full discussion of the scientific institutions created for the navy under Colbert.
16. Aulanier, *Histoire du palais et du musée du Louvre*, vol. 7, *Le Pavillon du roi* (1958), pp. 78–83.
17. The French Academy of Sciences is extensively discussed in Brown, *Scientific Organizations in Seventeenth Century France* (1934/1967); Hahn, *The Anatomy of a Scientific Institution* (1971); McClellan, *Science Reorganized: Scientific Societies in the Eighteenth Century* (1985); Sturdy, *Science and Social Status* (1995); and Passeron, “Une Séance à l’Académie” (1996).
18. The volume contained only two unremarkable memoirs concerning ship theory. Many original letters concerning the foundation and function of the Academy of Navy are in ANF Fonds Marine G 93 (Henrat, *Innovations techniques dans la marine* [1990], pp. 74–77). An extensive history is given in Doneaud du Plan, *Histoire de l’Académie de Marine* (1878). Other accounts may be found in Mascart, *La Vie et les travaux du Chevalier Jean-Charles de Borda* (1919), pp. 188–211; and Henwood, “La Première Académie de Marine” (1991).
19. A good comparative study of European societies is in McClellan, *Science Reorganized: Scientific Societies in the Eighteenth Century* (1985).
20. Frängsmyr, *Science in Sweden* (1989).
21. Stibolt, *Afhandling om skibes kiølbækkelighed* (1784). I thank Bjarne Stavnshøj, of the Royal Danish Academy Secretariat, for this information, and Jakob Seerup for his assistance in translation.
22. Johns, “An Account of the Society for the Improvement of Naval Architecture” (1910).

23. Maitz de Goimpy, *Traité sur la construction des vaisseaux* (1776); Vial du Clairbois, *Essai géométrique et pratique* (1776), and *Traité élémentaire de la construction des vaisseaux* (1782).
24. Murray, *Treatise on Ship-building and Navigation* (1754/1765); Hennert, *Cursus Matheseos Adplicatae* (1775); Anonymous, *The Shipbuilder's Repository* (1782/1992).
25. Vial du Clairbois, *Encyclopédie méthodique: Marine* (1783–1787/1987).
26. Bouguer, letter to Minister of the Navy Maurepas (13 January 1734).
27. Murat, *Colbert* (1980/1984), p. 172.
28. Anthiaume, *Le Navire* (1922/1980), p. 230. Spanish, Italian, and Irish naval officers also served in the French fleet; see Vergé-Franceschi, *La Marine française au XIII^e siècle* (1996), pp. 398–401.
29. Anthiaume, *Le navire* (1922/1980), pp. 231–232; Llinares, *Marine, propulsion et technique* (1994), pp. 53–54, 222; Dingli, *Colbert, Marquis de Seignelay* (1997), pp. 29–45.
30. Seignelay, “Remarque sur la marine d’Hollande” (1672).
31. Llinares, *Marine, propulsion et technique* (1994), p. 54.
32. Mémain, *La Marine de guerre sous Louis XIV* (1937), pp. 652–668; Lemineur, *Les Vaisseaux du Roi Soleil* (1996), pp. 41–44. The full texts for the 1670, 1671, and 1673 regulations are in Boudriot, *Les Vaisseaux 50 & 64 canons* (1994), pp. 16–17. A thorough discussion of Colbert’s attempts at standardization is in Peter, *Le Port et l’arsenal de Toulon sous Louis XIV* (1995), pp. 85–116.
33. Seignelay began signing naval dispatches under his father’s guidance in 1672 (Murat, *Colbert* [1980/1984], p. 182), and by 1678 he had essentially taken over from Colbert. La Roncière, *Un Tricentenaire: Un Grand Ministre de la marine, Colbert* (1919), p. 86.
34. Mémain, *La Marine de guerre sous Louis XIV* (1937), pp. 669–696; Lemineur: *Les Vaisseaux du Roi Soleil* (1996), pp. 45–46.
35. Colbert, letter to Arnoul, Demuyn, and de Seuil (1678). Colbert was, of course, overly admiring of the British Navy Board (even if he tacitly insulted their intelligence), which did not have any such “theory” in place. British constructors still worked quite independently at the time.
36. Colbert, letter to Duquesne (12 October 1678); Seignelay, letter to Duquesne (22 January 1680); Seignelay, letter to Duquesne (12 February 1680).
37. Lemineur, *Les Vaisseaux du Roi Soleil* (1996), pp. 217–220. The models were intended to be at 1/12 or 1/20 scale (i.e., between 2 and 4 meters in length).
38. Louis XIV’s attitude is neatly captured in the title of chapter III of La Roncière, *Un tricentenaire: Un Grand Ministre de la marine Colbert* (1919), pp. 43–76—“The Indifference of Louis XIV for the Navy.”
39. Stroup, “Louis XIV as Patron of the Parisian Academy of Sciences” (1992), pp. 226–227.

40. Ausseur, “Un Essai de construction préfabriqué au XVII^e siècle” (1971); Verin, “Spectacle ou experimentation (1987), and “L’Espreuve du vaisseau qui a esté faite à Toulon en sept heures” (1996).

41. Fennebresque, *La Petite Venise, histoire d’une corporation nautique* (1899), p. 6. Colbert would not live to see his interest in hydraulics satisfied; it was only in 1684, a year after he died, that the enormous hydraulics system was completed on the Seine at Marly, with 14 huge wheels pumping water 162 meters vertically, and feeding the gardens via a 25-kilometer-long system of cast-iron aqueducts.

42. Demerliac, *La Marine de Louis XIV* (1992), pp. 180–182.

43. A description of this nautical corporation is given in Fennebresque, *La Petite Venise* (1899); and Nolhac, *La Création de Versailles* (1925), pp. 289–309.

44. The spelling of the family name was by no means uniform; historians have used Eliçagaray, Elissagaray, and Elisagaray. Renau invariably referred to himself simply as “Renau” in his public writings. He appears to have spelled his name Elissaray on the birth certificate of a Catherine Favey on 25 July 1681 in Brest (Mascart, *La Vie et les travaux du Chevalier Jean-Charles de Borda* [1919], p. 625). The spelling Elizagaray comes from his signature on his last will and testament, although his brother Bertrand signed it Elicazaray, which was the name inscribed on the family’s house in Armendaritz (I thank the engineering historian Hélène Vérin for this information). Biographical details of Renau are found in Fontenelle, “Éloge de M. Renau” (1719); Turpin, *Histoire des illustres françois* (1792), vol. 2, pp. 50–82; Erlo, *Un Officier des armées de terre et de mer au temps de Louis XIV: Bernard Renau d’Elissagaray* (1905); Bagneux, *Un Basque illustre, Renau d’Elissagaray* (1932); and Bluche, *Dictionnaire du grand siècle* (1990), p. 1190.

45. Renau d’Elizagaray, “Mémoire sur les constructions des vaisseaux” (1679), p. 1.

46. See Ziggelaar, *Le Physicien Ignace Gaston Pardies* (1971).

47. Roberval’s proof was appended to Marin Mersenne’s 1636 treatise on musical acoustics, *Harmonicorum Libri* (Books of Harmonics). He created a more concrete demonstration in 1669–1670 with his new linked-arm balance (Dugas, *A History of Mechanics* [1955/1988], pp. 151–153). Pardies, who taught at the College of Clermont in Paris from 1670 to 1673, would have been aware of the teachings and experiments of Roberval, who from 1636 to 1675 was professor at the College of France, just a few blocks away.

48. Pardies, *La Statique; ou la Science des forces mouvantes* (1673), pp. 239–246.

49. Although Evangelista Torricelli had established the relationship of resistance to the square of velocity in the 1640s, it was not widely accepted at the time Pardies wrote *La Statique*.

50. Renau d’Elizagaray, *Mémoire sur les constructions des vaisseaux* (1679).

51. Dassié, *L’Architecture navale* (1677/1695/1994).

52. A short analysis of Renau’s *Mémoire* is given in Vérin, *La Gloire des ingénieurs* (1993), pp. 351–353. A longer analysis of it is under way (as of June 2005) by Hélène Vérin, Gérard Louyot,

and Jean-Jacques Brioist for eventual publication. I am indebted to them for their insights into Renau's arguments and rationale, much of which I have used for this section.

53. Renau d'Elizagaray, *Mémoire sur les constructions des vaisseaux* (1679), pp. 5–6.

54. Descartes, *Discours de la méthode pour bien conduire sa raison* (1637).

55. Hambly, *Drawing Instruments, 1580–1980* (1988), p. 89.

56. Boudriot, *Le Vaisseau trois-ponts du chevalier Tourville* (1998), p. 25.

57. Tourville had met Pangalo, originally from Naples or Sicily, in mysterious circumstances the year before. According to an implausible account written 70 years after the event, Pangalo was captured in his youth by corsairs and brought to Alger, where he was put to work in a boatyard. When Tourville moored there, Pangalo jumped into the ocean and swam 9 miles to the ship, and to freedom (Deslandes, "Sur la Construction des vaisseaux" [1747], pp. 2065–2066). Other sources claim that Tourville liberated Pangalo from a Tunis jail (Dessert, *Tourville* [2002], p. 161). However they came together, Tourville took Pangalo under his wing, and the two traveled together to various dockyards in France. Under Tourville's patronage, Pangalo quickly rose in stature, and became principal constructor at Brest in 1690.

58. The outlines of this plan are drawn from various dispatches of Seignelay, located in ANF Fonds Marine B2/42–43.

59. Seignelay encouraged Duquesne to come up with his theory in two letters (January and February 1680). In June 1680 Seignelay requested Tourville to enter into detail on his theory (Seignelay, letters to Duquesne, 22 January 1680 and 12 February 1680; Seignelay, letter to Tourville, 6 June 1680).

60. Boudriot, *Le Vaisseau trois-ponts du chevalier Tourville* (1998), p. 28.

61. The Toulon model was already being built at the direction of the intendant Pierre Arnoul, who was finally responding to Colbert's continued entreaties for a scale model of a ship of each rate. In this case, Arnoul succeeded in building only a single model of a second-rate ship. Anthiaume, *Le Navire* (1922/1988), p. 244; Lemineur, *Les Vaisseaux du Roi Soleil* (1996), p. 55.

62. On 1 September 1680 Seignelay instructed Demuyn, intendant of La Rochelle, to bring Pangalo's model to Versailles that winter, so that all constructors could give their advice on the proportions in order to create a set of rules to be observed for all vessels. Seignelay, letter to Demuyn (1 September 1680).

63. Boudriot, *Le Vaisseau trois-ponts du chevalier Tourville* (1998), pp. 25–26.

64. Anthiaume, *Le Navire* (1922/1988), pp. 244–246; Demerliac, *La Marine de Louis XIV* (1992), p. 181; Boudriot, *Le Vaisseau trois-ponts du chevalier Tourville* (1998), pp. 20–21. In addition to the size differences between the models, it is doubtful that any meaningful tests could have been made within the Grand Canal. The basin was 62 meters wide, only 6 times the length of *Modèle*; the boat never could have been maneuvered down the canal except in very particular wind con-

ditions. Certainly, the size of *Frégate* was more in keeping with the dimensions of the Grand Canal, but it was still a tight fit (a 12:1 ratio). By comparison, modern hobbyists who race models of fully rigged ships build them around 1.5 to 2.0 meters in length, and their racecourses are typically around 70 meters wide (i.e., a 35:1 ratio). The source documents from that period do not answer a number of questions that a modern naval architect would immediately ask. Did Colbert or Seignelay try to ensure that the dimensions of the two models matched? Did Tourville or Renau realize that *Modèle* was too big for the canal? In any event, the two models served to entertain Louis XIV through at least the turn of the century.

65. Colbert forbade any further expenditure on models, stating, “It is impossible to justify the construction of a vessel on the test performed that is done with a [model]. Cited in Boudriot, *Le Vaisseau trois-ponts du chevalier Tourville* (1998), pp. 20–21.

66. A pair of models was built and tested under Tourville's direction in Brest (June–August 1681): a conventional model built by Hubac, and *Ardente*, a replica of the ellipse ship *Modèle* built by Pangalo. However, the results of the comparison are not known (Demerliac, *La Marine de Louis XIV* [1992], p. 109; Boudriot, *Le Vaisseau trois-ponts du chevalier Tourville* [1998], p. 21). In early 1686, while in Toulon, Tourville tested a model of a conventional ship (*Hasardeux*) against one built to Hoste's ideas, which included the use of a semicircular bow and stern. Hoste's model did not perform well, and Hoste temporarily put aside his research into ship construction (Deslandes, “Seconde Lettre sur la construction des vaisseaux” [1748], pp. 421–425; Demerliac, *La Marine de Louis XIV* [1992], p. 110; Boudriot, *Le Vaisseau trois-ponts du chevalier Tourville* [1998], p. 21). However, there were no hard feelings between the two; Hoste became Tourville's confessor and fought with him in 1692 at the battle of La Hogue, and Tourville encouraged Hoste to renew his research on naval architecture, culminating in his 1697, *Théorie de la construction des vaisseaux*, discussed later in this work.

67. The *only* primary source document I have found that specifically asserts the existence of the construction conferences is in Seignelay, letter to Seuil (23 February 1681): “. . . the king, having assembled here the carpenters from all the ports and counties of the navy to examine the models of vessels which were made in Rochefort and Toulon, and to decide for once their proportions that one must give to his Majesty's [ships]; it is hoped that M. Hubac can be here to give his advice . . . but since he is old . . . make certain his son takes his place.” The other primary source documents are a letter from Seignelay a few weeks later, again asking for Hubac (Seignelay, letter to Seuil [15 March 1681]); another letter stating that on 9 April, Duquesne left for Toulon (Seignelay, letter to Vauvray [9 April 1681]); and a third letter stating that Hubac left for Brest a week after that (Seignelay, letter to Seuil [14 April 1681]). The rest of the accounts are secondary sources written years or centuries after the events, each author having a different interpretation of the purpose and outcome of the conferences: Fontenelle, “Éloge de M. Renau” (1719), pp. 102–103; Bouguer, *Traité du navire* (1746), pp. vii–ix; Anthiaume, *Le Navire* (1922/1988), p. 268; Bagneux, *Un Basque illustre: Renau d'Elissagaray* (1932), pp. 6–7; Mémain, *La Marine de guerre sous Louis XIV* (1937), pp. 709–713; Vérin, *La Gloire des ingénieurs* (1993), pp. 335–339; Lemineur, *Les Vaisseaux du Roi Soleil* (1996), p. 224; Boudriot, *Le Vaisseau trois-ponts du chevalier Tourville* (1998), p. 17.

68. In Renau's eulogy, the secretary of the Academy of Sciences, Bernard le Bouyer de Fontenelle, paints a picture of the conferences in which the brave but doddering Duquesne bows before the brilliant theories of young Renau (Fontenelle, "Éloge de M. Renau" [1719], p. 103). Renau's biographies have tended to pick up that theme, making it quite difficult to properly sort out what actually transpired. It would appear likely that Renau's success was due in a large measure to his close connections with the Colbert family; he was, as stated, something like a cousin to Colbert, and therefore also a cousin to the count of Vermandois.

69. I am grateful to Ben Trotter for information on the movements of Vauban during this period.

70. The original idea for attacking Alger with mortar ships was developed by Chevalier Paul in 1661, but he never saw it through. Bluche, *Dictionnaire du grand siècle* (1990), pp. 639, 1164, 1190.

71. For further reading on mortar ships and their use in naval sieges, see Boudriot and Berti, *La Salamandre* (1982/1991); Peter, *Les Barbaresques sous Louis XIV* (1997), *Les Artilleurs de la marine sous Louis XIV* (1995), and *Une Stratégie de la terreur sous Louis XIV, les galiotes à bombes*, accessed May 2003.

72. Du Hamel, "Invention de M. Renault" (1681), *HMAS* (1681), p. 330.

73. Bouguer, *Traité du navire* (1746), pp. viii–ix.

74. Fincham, *A History of Naval Architecture* (1851/1979), p. xiii.

75. Boudriot, *Les Vaisseaux 50 & 64 canons* (1994), pp. 15, 18.

76. Lemineur, *Les Vaisseaux du Roi Soleil* (1996), p. 63.

77. Boudriot, *Les Vaisseaux 74 à 120 canons* (1995), p. 17.

78. Mémain, *La Marine de guerre sous Louis XIV* (1937), p. 712.

79. Renau d'Elizagaray, "Mémoire du Sr Renau sur les constructions" (February 1684).

80. Renau supervised the construction of ellipse ships during two periods: 1681–1683 and 1690–1694. The ellipse ships of the first period were apparently the 58-gun *Arrogant* and its sister *Brave*, built by Salicon and Doley at Le Havre in 1682–1683; and the 56-gun *Apollon*, built by Hubac and Pangalo at Brest in 1681–1682. The first mortar ships (1682–1683) may have also been "ellipse ships." The second period comprised the 68-gun *Ecueil*, built by René Vasseur at Dunkirk (1690–1691); the 14-gun *Serpente*, which Renau built at Le Havre (1691–1692); and the 56-gun *Bon*, built by Jean-Pierre Le Brun at Brest (1693–1694). Jean-Pierre's son François Le Brun, at Lorient, independently built two ships to Renau's concept: the mortar ship *Foudroyante* (1695) and the Compagnie de Lorient ship *Perle d'Orient* (1699). However, no plans of these ships survive to show with assurance that they had elliptical hull lines. Beauchesne, *Historique de la construction navale à Lorient* (1980), pp. 14–15; Demerliac, *La marine de Louis XIV* (1992), pp. 18, 25, 28, 52, 59, 60, 190; Boudriot, *Le Vaisseau trois-ponts du chevalier Tourville* (1998), p. 26.

81. There was some cross-pollination between dockyards; for example, Pangalo and the Hubac family at Brest, and François Pomet in Rochefort, began working in Toulon before moving to the

Atlantic coast, bringing Mediterranean design methods with them. See Rieth, “Le Cas de la France à la fin du XVII^e siècle” (2001).

82. Renau d’Elizagaray, *De la Théorie de la manoeuvre des vaisseaux* (1689).

83. Renau d’Elizagaray, “Réponse de M. Renau à M. Huguens” (1694), pp. 593–594.

84. Renau d’Elizagaray, “État des seices de Renau” (1687). At the same time, Renau requested an annual pension of 2,000 *livres tournois* (about \$20,000 today) for his services.

85. Vauban, letter to Louvois (14 November 1688).

86. A letter in the 1747, *Journal de Trévoux* claimed that, according to the Brest hydrographer Guillaume Coubard, Renau outlined the principles in the book but it was Sauveur who actually wrote it, because Renau was incapable of carrying out the work (Deslandes, “Lettre écrite à M. de C. sur la construction des vaisseaux” [1747], pp. 2066–2067). It is, however, hard to reconcile this uncharitable criticism with Renau’s later, spirited defense against Huygens.

87. Renau d’Elizagaray, *De la Théorie de la manoeuvre des vaisseaux* (1689), pp. 13–14.

88. In general, the hull can be modeled as a symmetrical foil moving at an angle of attack through the water in order to derive the resultant forces, either experimentally or using computational fluid mechanics. Renau’s guess that the lateral resistance (side force) is 100 times greater than forward resistance (drag) was well off the mark. For a sailing yacht, the ratio of side force to drag varies from about 3.0 to 9.0, depending on the speed and yaw of the vessel. Herreshoff, “Hydrodynamics and Aerodynamics of the Sailing Yacht” (1964), p. 459.

89. Renau d’Elizagaray, *De la Théorie de la manoeuvre des vaisseaux* (1689), pp. 28–29.

90. La Roque, review of *De la Théorie de la manoeuvre des vaisseaux* (1689); Mencke, review of *La Théorie de la manoeuvre des vaisseaux* (1690).

91. Pepys, *Samuel Pepys’s Naval Minutes* (1926), p. 390. Pepys wrote this note to himself on 27 April 1694. I thank the science historian Rob Iliffe for alerting me to this passage.

92. Hoste, *Recueil des traités de mathématique* (1692), vol. 3, *Traité de la maneuvre des vaisseaux*, pp. 71–178.

93. *Ibid.*, pp. 71–72. Hoste may have been disingenuous when he failed to mention the name of the author, as he likely knew Renau personally. Both were close colleagues of Tourville, and their paths would have crossed in Toulon around 1685–1686, when Renau had worked with Pangalo while Hoste was a mathematics instructor for the Navy Guards and had built his model to test against Tourville’s.

94. Hoste, *Traité des évolutions navales* (1691), and *Art des armées navales* (1697).

95. Huygens, *Oeuvres complète*, vol. 21 (1950), pp. 327–341.

96. Cited in a letter to L’Hôpital (25 November 1683). Huygens, *Oeuvres complète*, vol. 10 (1905), p. 553.

97. Huygens, *Oeuvres complètes*, vol. 10 (1905), pp. 478, 523–524, 553.
98. Huygens, *Oeuvres complètes*, vol. 21 (1950), pp. 345–353, and “Remarque de M. Huguens sur le livre de la Manoeuvre des Vaisseaux imprimé à Paris en 1689” (1693/1905). Huygens usually spelled his own name Huguens or Hugens, but Huygens is the universally accepted orthography.
99. Huygens, *Oeuvres complètes*, vol. 10 (1905), pp. 585, 624; Renau d’Elizagaray, “Réponse de M. Renau à M. Huguens” (1694/1905).
100. Huygens, “Réplique de Mr. Huguens à la reponse de Mr. Renau” (1694).
101. Huygens, *Oeuvres complètes*, vol. 10 (1905), pp. 653–654, 690–693, and “Raisons qu’a M. Huguens pour se plus continuer la dispute avec M. Renau” (1694/1905).
102. Renau d’Elizagaray and Huygens, *Réplique de M. Huegens à la réponse de M. Renau* . . . (1694).
103. Huygens, *Oeuvres complètes*, vol. 10 (1905), pp. 642–643, 658, 686–687, 704–706, and vol. 21 (1950), pp. 162–163; Johann Bernoulli, *Der Briefwechsel von Johann Bernoulli* (1955), pp. 230, 231, 237, 238, 240–243, 246, 249, 251, 255.
104. Jacob Bernoulli, “Explicationes, Annotationes et Additiones” (1695), “Problema Beaunianum Universalis Conceptum” (1696); “De Celeritate et Declinatione (*dérive*) Navis” (1744), and “Celeritates Navis a Quiete Inchoatas Usque ad Maximam Invenire” (1744).
105. Johann Bernoulli, *Der Briefwechsel von Johann Bernoulli* (1955), pp. 326, 332.
106. For an excellent overview of this facet of scientific writing, see Dascal and Marras, *The République des Lettres: A Republic of Quarrels?*, Accessed December 2001.
107. Huygens, “Remarque de M. Huguens . . .” (1693).
108. The first analyses were given in Parent, *Éléments de mécanique et de physique* (1700), pp. 369–373, and *Recherches de mathématique et de physique* (1705), vol. 2, pp. 741–759, in which he examined the speed and route of a horizontal planar figure “in one fluid moved by another fluid,” and the optimum angle of the rudder, using fairly complex geometry; he claimed that his results were not much different from Pardies’s, Renau’s or Huygens’s. In his second analysis (Parent, “Premier Problème de la manoeuvre” [1714]), he determined the speed and movement of a vertical sail pushed by the wind, this time using differential calculus, which was just becoming widely known.
109. The debate was reported in the following works: Elvius, “Vetenskapernas historia om mekanismen uti skeppens fart” (1747); Müller, translation of Duhamel du Monceau *Éléments de l’architecture navale* as *Anfangsgründe der Schiffbaukunst* (1791/1973), pp. xv–xvii; Montucla, *Histoire des mathématiques* (1802/1968), vol. 4, pp. 410–417; Fincham, *A History of Naval Architecture* (1851/1979), pp. xii–xv; Hahn, *L’Hydrodynamique au XVIII^e siècle* (1965), pp. 12–13; Boudriot, *Le Vaisseau trois-ponts du chevalier Tourville* (1998), p. 20. Voltaire’s comment is from *Lettres philosophiques* (1734), p. 285.

110. Renau d'Elizagaray, *Mémoire où est démontré un principe de la mécanique des liqueurs* (1712). No date, publisher, or city was provided in the book; given this lack of information, plus its small size and apparently low numbers of copies (it is very hard to find today, except on Internet databases), it is possible that Renau published it himself. The assumed date of publication comes from Montucla, *Histoire des mathématiques* (1802/1968), vol. 4, p. 412.

111. Anonymous, review of *Mémoire où est démontré un principe de la mécanique des liqueurs* (1713).

112. Johann Bernoulli, *Essay d'une nouvelle théorie de la manoeuvre des vaisseaux* (1714).

113. Bouguer, letter to Maurepas (1727).

114. Johann Bernoulli's *Essay d'une nouvelle théorie* is extensively analyzed in Costabel, "Une Leçon magistrale de Jean I Bernoulli" (1957), from which this quote derives. A more succinct analysis is provided in Montucla, *Histoire des mathématiques* (1802/1968), vol. 4, pp. 412–417.

115. Daniel Bernoulli, "Examen Principiorum Mechanicae" (1726/1987). This is also discussed in chapter 3. I thank Jean Dhombres for his further explanations on the history of vector analysis.

116. An account of this failed fiscal experiment is given in Fracard, "Une Disciple basque de Vauban, Renau d'Elissagaray" (1967).

117. Fontenelle, "Éloge de M. Renau" (1719), p. 119. Hyponatremia is caused by overloading the body with fluids, which dilutes sodium levels (electrolytes) in the blood and can cause brain swelling. It is a common condition nowadays among long-distance runners who drink too much water without replacing the electrolytes. In extreme cases, the combination of imbalanced electrolytes and brain swelling can result in coma and death. I am grateful to the infectious disease specialist James Campbell for his useful insights.

118. Parent, "Analyse d'un nouveau livre intitulé *Essay d'une nouvelle Théorie*" (1715), and "Résolution de trois problèmes célèbres tentés par M. Bernoulli" (1715).

119. Hermann, *Phoronomia* (1716), vol. 2, pp. 356–361.

120. MacLaurin, *A Treatise on Fluxions* (1742), vol. 2, pp. 734–739.

121. Onzembray, "Machine pour connoître sur mer l'angle de la ligne du vent et de la quille du vaisseau" (1731). Otherwise known as Louis Léon Pajot, count of Ons-en-Bray, the author was best known for his perfection of the metronome.

122. Pitot, "Règles ou loix générales des impulsions obliques des fluids" (1727).

123. Pitot, *La Théorie de la manoeuvre des vaisseaux* (1731).

124. *Ibid.*, p. 80.

125. Savérien, *Nouvelle Théorie de la manoeuvre des vaisseaux* (1746/1747). Savérien would later publish a nautical dictionary (*Dictionnaire historique: Théorique et pratique de marine* [Paris: Jombert, 1758]) and several works on philosophy.

126. Muller, *Appendix or supplement to the Treatise of artillery* (1768), pp. 85–88, gave some angles of rudders and sails for greatest effectiveness. Muller was a mathematics professor at the British Royal Military Academy in Woolwich.

127. See Rodger, “Image and Reality in Eighteenth-Century Naval Tactics” (2003), for an excellent analysis of the difference between tactical theory and actual practice in sailing warships.

128. Bouguer, “Sur de Nouvelles Courbes ausquelles on peut donner le nom de lignes de poursuite” (1732).

129. Maupertuis, “Sur les Coubres de poursuite” (1732).

130. Bouguer, *Traité du navire* (1746), pp. 416–472.

131. For example, in 1748 he wrote a letter in *Journal de Trévoux* explaining, without recourse to mathematics, how a ship can sail faster than the wind. Bouguer, letter on the speed of ships (1748).

132. Euler, *Scientia Navalis* (1749), pt. 2, pp. 201–230 and 421–459, and *Théorie complete de la construction et de la manoeuvre des vaisseaux* (1773), pp. 130–159 and 182–261.

133. Juan y Santacilia, *Examen marítimo* (1771/1992), vol. 2, pp. 376–389.

134. Bouguer, “Mémoire sur la forme des corps les plus propres à tourner sur eux-mêmes” (1751).

135. Bouguer, “Solutions des principaux problèmes de la manoeuvre des vaisseaux” (1754). The French mathematician Alexis Clairaut would provide a simpler method of obtaining the same result in a 1760 Academy of Sciences paper. Clairaut, “Nouvelle Solution des quelques problèmes sur la manoeuvre des vaisseaux” (1760).

136. Bouguer, “Seconde Mémoire sur les principaux problèmes de la manoeuvre des vaisseaux” (1755).

137. Bouguer, *De la Manoeuvre des vaisseaux* (1757).

138. *Ibid.*, pp. vi–x. The French Navy Academy became “Royal” in 1769.

139. *Ibid.*, pp. 337–347.

140. Penzo, *Navi Veneziane/Venetian Ships* (2000), p. 39. I thank the professional translator Sonja Cutler for her assistance in deciphering this drawing.

141. Bourdé de Villehuet, *Le Manoeuvrier* (1765/1769). Two years prior, Sébastien-François Bigot de Morogues, instructor of the Naval Guards and director of the Academy of the Navy, had written *Tactique navale* (Naval Tactics), but this dealt principally with naval signals as opposed to maneuvering theory.

142. Harland, *Seamanship in the Age of Sail* (1984), pp. 61–62.

143. A more thorough analysis is given in Simón Calero, *La Génesis de la mecánica de los fluidos* (1996), pp. 360–373, upon which most of my conclusions are based.

144. Huygens, *Oeuvres complètes*, vol. 1 (1888), pp. 35–40.
145. Pardies, *La Statique ou La Science des forces mouvantes* (1673), p. 164.
146. Huygens, *Oeuvres complètes*, vol. 10 (1905), p. 133.
147. Ibid., pp. 437–440, 556–563, 621–629.
148. Jacob Bernoulli, “Curvatura Veli” (1692) “Explicationes, Annotationes et Additiones” (1695) and “Problema Beaunianum Universalius Conceptum” (1696).
149. Bouguer, *Traité du navire* (1746), pp. 349–353, and *De la Manoeuvre des vaisseaux* (1757), pp. 189–194.
150. Euler, *Scientia Navalis* (1749), pt. 2, pp. 321–377, and *Théorie complete de la construction et de la manoeuvre des vaisseaux* (1773), pp. 160–168.
151. Juan y Santacilia, *Examen marítimo* (1771/1992), vol. 2, pp. 557–575 and app. 1. An in-depth analysis of this work is also given in Simón Calero, “La mecánica de los fluidos en Jorge Juan” (2001), pp. 259–262, 268–269.
152. Harland, *Seamanship in the Age of Sail* (1984), p. 60.
153. Literally dozens of books cover the evolution of sailing rig, but two handy guides are McGowan, *Tiller and Whipstaff: The Development of the Sailing Ship 1400–1700* (1981); and Gardiner and Unger, *Cogs, Caravels and Galleons: The Sailing Ship 1000–1650* (1994).
154. Aristotle, *Complete Works* (1984), vol. 2, p. 1305.
155. Hoste, *Théorie de la construction des vaisseaux* (1697), p. 49.
156. Mairan, “Reception of Bouguer’s Treatise on Masting” (1724).
157. Mairan, “Remarks on Bouguer’s Treatise, Entitled ‘L’Art de mâter les vaisseaux 1^{re} Partie” (1724). “Part 2” was never presented to the Academy, although it eventually appeared as the “Additions” section of his 1727 prize entry.
158. Mairan, “Lettre de M. de Mairan à M. l’Abbé Bignon” (1728).
159. Bouguer, letter to Maurepas (1727).
160. Bouguer, “De la Mâtüre des vaisseaux” (1727); Euler, “Meditationes Super Problemate Nautico” (1727); Camus: “De la Mâtüre des vaisseaux” (1727).
161. I am grateful to Dirk Wintergruen and Horst Nowacki for their descriptions of Euler’s unpublished diaries.
162. Euler, “Meditationes Super Problemate Nautico” (1727).
163. An analysis of Euler’s prize entry is given in Habicht, “Einleitung zu Band 20 der zweiten Serie” (1974), pp. viii–xv.
164. A full analysis of Bouguer’s prize entry is given in Lamandé, “Théorie et pratique maritimes dans deux textes de Pierre Bouguer” (1999).

165. Bouguer, *De la Mâtüre des vaisseaux* (1727/1728), pp. 121–123.
166. I thank Jean Dhombres for this insight.
167. Llinares, *Marine, propulsion et technique* (1994), pp. 93–95.
168. Beauchesne, *Historique de la construction navale à Lorient* (1980), p. 171.
169. Bouguer, *Traité du navire* (1746), pp. 387–388, 503–551.
170. *Ibid.*, pp. 515–516.
171. Savérien, *La Mâtüre discutée et soumise a des nouvelles loix* (1747). The book was reviewed for approbation by the Academy of Sciences by Bouguer's colleague Alexis Clairaut, who pointedly wrote on the *privèlege* page that he “did not admit of the views of the author.”
172. Bouguer, “Éclaircissemens sur le problème de la mâtüre des vaisseaux” (1745). The memoir was actually written in 1748 but backdated to the 1745 edition of the Academy memoirs, which were not published until 1749. This little example demonstrates the problem of providing dates for some texts.
173. A short analysis of this memoir is given in Lamandé, “Théorie et pratique maritimes dans deux textes de Pierre Bouguer” (1999), pp. 383–385.
174. Elvius, “Undersökning huru vida jämnvigt-punctens” (1747).
175. Euler, *Scientia Navalis* (1749), pt. 2, pp. 378–420, and *Théorie complete de la construction et de la manoeuvre des vaisseaux* (1773), pp. 169–181. Interestingly, Jorge Juan y Santacilia, always skeptical of the utility of theory in real ship design, never mentioned the *point vélique* in his *Examen marítimo*.
176. *Point vélique* was the title of a 1950 book of poems by Henri Pichette, and of a 1965 novel by Jean Pérol.
177. Harland, *Seamanship in the Age of Sail* (1984), p. 60.
178. Thévenard, *Mémoires relatifs à la marine* (1800), vol. 1, pp. 283–367.
179. Chevillard and Clairan-Deslauriers, letter to Duhamel du Monceau (1765); Boudriot, *Les Vaisseaux 50 & 64 canons* (1994), p. 58.
180. Forfait, *Traité élémentaire de la mâtüre des vaisseaux* (1788).
181. Boudriot, *La Frégate dans la marine française* (1992/1993), p. 260, and *Les Vaisseaux 74 à 120 canons* (1995), pp. 169, 184, and 205.

Chapter 3: A Shock to the System

1. The outline of this chapter generally follows that of the excellent text on the overall subject, *La génesis de la mecánica de los fluidos* (The Genesis of Fluid Mechanics), by Julián Simón Calero (1996). I am also indebted to Julián, as well as to Steven Gaukroger and Tom Wright, for their critiques.

2. An extensive treatment of early hydraulics and the central role played by Italian scientists is given in Maffioli, *Out of Galileo: The Science of Waters 1628–1718* (1994).
3. Most of these concepts are discussed in Mach, *The Science of Mechanics* (1893/1960); Duhem, *The Evolution of Mechanics* (1903/1980); Dugas, *A History of Mechanics* (1955/1988); Truesdell, “The Rational Mechanics of Flexible or Elastic Bodies” (1960); Dijksterhuis, *The Mechanization of the World Picture* (1961); and Truesdell, *Essays in the History of Mechanics* (1968).
4. Aristotle, *Complete Works* (1984), vol. 2, p. 1305.
5. Hoste, *Théorie de la construction des vaisseaux* (1697), pp. 48–49.
6. The controversy between vortices and gravitation is discussed in Aiton, *The Vortex Theory of Planetary Motions* (1972); and Fauque, “Tourbillons ou attractions: Les Physiciens du XVIII^e siècle entre un monde plein et un monde vide” (1992). A complete analysis of the development of the theory of the Earth’s shape is found in Greenberg, *The Problem of the Earth’s Shape from Newton to Clairaut* (1995).
7. Daniel Bernoulli, “Examen Principiorum Mechanicae” (1726/1987).
8. Euler, *Opera Omnia* (Complete Works), in four series; the first volumes were published in 1911 and publication continues as of this writing (2005).
9. Biographical sketches of Euler are in Calinger, “Leonhard Euler, The First St. Petersburg Years” (1996); and Dunham, *Euler: Master of Us All* (1999).
10. See Truesdell, “Rational Fluid Mechanics (1687–1765)” (1954), “Rational Fluid Mechanics (1765–1788)” (1955), and “Euler’s Contribution to the Theory of Ships and Mechanics” (1983); and Vischer, “Daniel Bernoulli and Leonhard Euler: The Advent of Hydromechanics” (1987).
11. None of this attraction came from any affinity for the sea; Euler was a landlubber all his life. Some biographies assert that he served as a medical officer in the Russian navy, but there is no evidence to support this. I thank the science historian Gleb Mikhailov for this information.
12. Thirriot, “Pouvoir politique et recherche hydraulique en France aux XVII^e et XVIII^e siècles” (1987).
13. Reuss, *Repertorium Commentationum a Societatibus Litterariis Editarum* (1801–1821/1961).
14. The origins of the phrase “cod’s head and mackerel’s tail” are unclear. It appeared nowhere in Baker’s manuscript “Fragments of Ancient English Shipwrighty”; the text below his drawing in figure 3.6 makes no mention of the fish. It is a description of the ship, which is about 178 tons, and of proportional changes from one size of ship to another, including differences in tonnage to quantities needed for frame timbers and planking. My thanks to Richard Barker for illuminating this almost unreadable passage.
15. A “Digression Concerning Shipping and Navigation” from the British poet John Dryden’s 1667 epic about the Anglo-Dutch war and the London fire, “Annus Mirabilis: The Year of Wonders (1666)” (Dryden, *The Poems of John Dryden* [1935], p. 35).

16. Quote from Admiral François-Edmond Paris in Needham, *Science and Civilisation in China*, vol. 3 (1961), pp. 418–419.

17. Quoted in Wright, “Ship Hydrodynamics 1710–1880” (1983), p. 24.

18. Pepper, “Harriot’s Manuscript on Shipbuilding and Rigging (ca. 1608–1610)” (1981).

19. Wallis, *Cono-cuneus or the Shipwright’s Circular Wedge* (1684); this first appeared as a booklet and then was appended to his *Treatise of Algebra* (1685).

20. Although the British constructor William Sutherland described the cono-cuneus as “a good foundation for the art of shipbuilding” (Sutherland, *The Ship-Builder’s Assistant* [1711], p. 2), he later noted that “it’s not made a general method; neither doth it stand good with the opinion of divers famous writers” (Sutherland, *Britain’s Glory* [1717], p. xxv). My thanks to the water engineer Richard Barker for alerting me to these passages.

21. Wallis, “A Discourse Concerning the Measure of the Air’s Resistance to Bodies Moved in It” (1688).

22. Huygens, *Oeuvres Complètes*, vol. 19 (1937), pp. 122–127. These towing experiments were recorded in the Registers of the Oral Proceedings of the Academy of Sciences, which were handwritten internal documents that were only briefly alluded to in the *History and Memoirs of the Academy* (HMAS [1698], p. 49).

23. Mariotte, *Traité du mouvement des eaux* (1686); Simón Calero, *La génesis de la mecánica de los fluidos* (1996), p. 105.

24. Simón Calero, *La génesis de la mecánica de los fluidos* (1996), pp. 108–116.

25. In the words of the science historian I. Bernard Cohen, the *Principia* was received by “a wholly unexpectant and unprepared audience who did not, in actual fact, know what to make of it or how to use it for some time.” Cohen, *Revolution in Science* (1985), p. 127.

26. Newton, *The Principia* (1687/1999), pp. 724–761.

27. This analysis of Newton’s derivation of fluid resistance, and the frustrum and solid of least resistance, is derived from the following sources: Forsyth, “Newton’s Problem of the Solid of Least Resistance” (1927), pp. 75–86; Cohen, “Isaac Newton, the Calculus of Variations, and the Design of Ships” (1974); Whiteside, *The Mathematical Papers of Isaac Newton*, vol. 6 (1974), pp. 456–480; Wright, “Ship Hydrodynamics 1710–1880” (1983), pp. 12–19; Chandrasekhar, *Newton’s Principia for the Common Reader* (1995), pp. 555–578; Arrington, “The Solid of Least Resistance: An Example from Newton’s *Principia*” (1997); Edwards, *Newton’s Nose-Cone Problem*, accessed August 2000.

28. Newton, *The Principia* (1687/1999), pp. 729–730. A scholium is a note amplifying a proof or course of reasoning.

29. It is worth noting here that the bows of modern torpedoes, which are generally quite fast, look rather like Newton’s solid and have a flat nose; but this is because of the need for a forward-looking planar sonar array and not because a flat-nosed body has “least resistance.” In fact, the

flat nose does cause greater resistance than a hemispherical or parabolic one, but the penalty is small and outweighed by the need for good sonar performance.

30. This interpretation of Newton's statement is also held by Cohen in his article "Isaac Newton, the Calculus of Variations, and the Design of Ships" (1974). Cohen also provides background on Newton's interest in ship construction; for example, he (Newton) had laboriously copied a manuscript on proportions of masts, rigging, and hull dimensions, described in Barker, "A Manuscript on Shipbuilding, Circa 1620, Copied by Newton" (1994).

31. Huygens independently reproduced Newton's results in 1691, but never published them. Huygens, "Résistances éprouvées par des surfaces" (1691/1950).

32. Whiteside, *The Mathematical Papers of Isaac Newton*, vol. 6 (1974), p. 466.

33. The British mathematician Andrew Forsyth demonstrated that, using modern analytical methods, there is in fact "*no solution of the problem to determine the shape of a solid of revolution undergoing a minimum of resistance, whether friction be taken into account or be ignored.*" Forsyth, "Newton's Problem of the Solid of Least Resistance" (1927), p. 83. Author's italics.

34. The following description of the debate over the solid of least resistance is derived from Montucla, *Histoire des mathématiques* (1802/1968), vol. 1, p. 130, and vol. 2, pp. 478–483; and from Whiteside, *The Mathematical Papers of Isaac Newton*, vol. 6 (1974), pp. 466–468.

35. Moivre, "Specimina Quaedam Illustria Doctrinae Fluxionum" (1695).

36. Fatio de Duillier, *Lineae Brevissimi Descensus Investigatio Geometrica Duplex, Cui Addita Est Investigatio Geometrica Solidi Rotundi in Quod Minima Fiat Resistentia* (1699).

37. Ibid., p. 18.

38. A thorough examination of the calculus priority dispute can be found in Alfred Rupert Hall's *Philosophers at War: The Quarrel Between Newton and Leibniz* (Cambridge: Cambridge University Press 1980).

39. L'Hôpital, "Méthode facile pour trouver un solide rond" (1699).

40. L'Hôpital, "Facilis & Expedita Methodus Inveniendi Solidi Rotundi" (1699/1968).

41. Johann Bernoulli, "Excerpta Litteris" (1699/1968).

42. Johann Bernoulli, "De Solido Rotundo Minimae Resistentiae" (1700/1968).

43. Fatio de Duillier, "Excerpta ex Responsione dn Nic. Fatii Duillierii ad Excerpta ex Literis Dn Joh. Bernoulli" (1701).

44. Craig, "Epistola ad Editorem" (1700/1701).

45. Fatio de Duillier, "Epistola Nicolai Fatij . . . qua Vendicat Solutionem Suam Problematis de Inveniundo Solido Rotundo" (1714).

46. For example, Hayes, *Treatise of Fluxions* (1704), pp. 146–150; and MacLaurin, *A Treatise on Fluxions* (1742), vol. 2, p. 751.

47. Saint-Jacques de Silvabelle, “Du Solide de la moindre résistance” (1760). In fact, his solution was not greatly different from those posed by L’Hôpital and Bernoulli.
48. An excellent overview of the process of interpreting Newton is given in Guicciardini, *Reading the Principia* (1999).
49. Sutherland, *The Ship-Builder’s Assistant* (1711), p. 2 and *Britain’s Glory: or, Shipbuilding Unvail’d* (1717), vol. 1, pp. 1–2. I thank Richard Barker for alerting me to these passages.
50. Hoste, *Théorie de la construction des vaisseaux* (1697), pp. 6–41.
51. Reyneau, *Analyse démontrée* (1708), vol. 2, pp. 398–405.
52. Bouguer, “De la mâture des vaisseaux” (1727/1728), pp. 121–123.
53. Ibid., pp. 155–164. The young Bouguer was by then already well known to Reyneau, who had recommended him to the Academy of Sciences to assist with a study on admeasurement (discussed further in chapter 4).
54. Bouguer, “Une Base qui est exposée au choc d’un fluide étant donnée” (1733); Simón Calero, *La génesis de la mecánica de los fluidos* (1996), pp. 356–360.
55. Bouguer, letter to Bignon (1733). Bouguer requested additional funds from Minister of the Navy Maurepas for the experiments he was doing on the shock of fluids and the strength of ropes; he claimed the cost was “almost nothing” because he employed royal dockyard workers during their idle moments. Bouguer also was developing his concepts of the metacenter at this time (described in chapter 4).
56. Bouguer, *Traité du navire* (1746), pp. 363–416, 572–682.
57. Bouguer, “De l’Impulsion des fluides sur les proues” (1746).
58. Euler, *Scientia Navalis* (1749/1967), pt. 1, pp. 195–342.
59. Bouguer, *Traité du navire* (1746), p. 357; Euler, *Scientia Navalis* (1749/1967), pt. 1, p. 198; Euler, *A Compleat Theory of the Construction and Properties of Vessels* (1776), pp. 78–79; Simón Calero, *La génesis de la mecánica de los fluidos* (1996), pp. 218–219, 351–352.
60. Euler, *Scientia Navalis* (1749/1967), pt. 1, p. 291.
61. However, Bouguer developed equations of resistance for pyramidal bows in his Academy of Sciences memoir “De l’Impulsion des fluides sur les proues,” published the same year 1746 as *Traité du navire*.
62. Bouguer, *Traité du navire* (1746), pp. 387–391.
63. Note that actual resistance would be “impulsion” times ρv^2 .
64. Bouguer, *Traité du navire* (1746), pp. 418–421.
65. Euler, *Scientia Navalis* (1749/1967), pt. 1, p. 304.
66. Bouguer, *Traité du navire* (1746), p. 578.

67. Ibid., p. 617.
68. Ibid., pp. 636–653; Simón Calero, *La génesis de la mecánica de los fluidos* (1996), pp. 214–215.
69. Sutherland, *Britain's Glory* (1717), p. xxvi. No plans of *Royal Katherine* are known to exist; the earliest ones at the National Maritime Museum Ship Plans Collection in Woolwich date from the late 1600s.
70. See, for example, Robertson, *The Evolution of Naval Armament* (1921/1968), pp. 35–36.
71. McGee, “Ships and Science” (1999), p. 40.
72. Birch, *The a History of the Royal Society* (1757/1968), vol. 1, pp. 183–192; McGee, “Ships and Science” (1999), p. 39.
73. Beauchesne, *Historique de la construction navale à Lorient* (1980), p. 33. Gobert claimed to have incorporated other innovations into the ship, such as diagonal planking to improve strength and the newly invented rudder wheel, developed around 1703 in Britain as an improvement over the tiller.
74. Geslain, “Extrait des ouvrages” (1732); Ollivier, *Remarques sur la marine des anglois et hollandois* (1737/1992), p. 29. In Geslain’s text the name is spelled “Raisinquentre,” which is undoubtedly a mis-hearing of “Isaac Newton.”
75. Ollivier, *Remarques sur la marine des anglois et hollandois* (1737/1992), pp. 182–184.
76. Ibid. No plans specific to the *Eltham* are known to exist; it was part of the 1733 establishment, although evidently a rebuild with different dimensions than other ships of that class. Lyon, *The Sailing Navy List* (1993), p. 48.
77. Quoted in Klemm, *A History of Western Technology* (1959), p. 262.
78. Charnock, *A History of Marine Architecture*, vol. 2 (1800), p. 405. It is possible that Charnock was referring to either the 38-gun frigate *HMS Minerva*, laid down in 1778 and launched in 1780, or the 32-gun *HMS Andromeda*, built in 1777 at Cowes, which was quite sensitive to trim—as was its sister ship *HMS Acme*—and sailed best when its forward guns were brought all the way aft. Gardiner, *The First Frigates* (1992), p. 100.
79. Marzari, “L’arte della progettazione e della costruzione navale a Trieste” (1998), pp. 183, 190. According to a contemporary report, Panfilli did so after visiting Cartagena in Spain, possibly after meeting the Spanish constructor Jorge Juan y Santacilia and learning of the methods from him.
80. Bouguer, *Traité du navire* (1746), pp. 378–396.
81. Duhamel du Monceau, *Éléments de l’architecture navale* (1752/1758/1994), pp. 365–381.
82. Cochet, “Calcul d’un vaisseau de 60 canons” (1754). This document is in the Duhamel du Monceau collection (MH 25) of the Phillips Library, Peabody-Essex Museum, Salem, Mass., which contains several examples of detailed resistance calculations submitted by constructors during the 1750s–1770s.

83. Duhamel du Monceau, *Éléments de l'architecture navale* (1752/1758/1994), pp. 390–392.
84. Euler, *A Compleat Theory of the Construction and Properties of Vessels* (1776), p. 94.
85. Daniel Bernoulli, *Hydrodynamica* (1738/1968).
86. Daniel Bernoulli, "Theoria Nova de Motu Aquarum per Canales Quosunque Fluentium" (1727).
87. See especially Truesdell, "Rational Fluid Mechanics (1687–1765)" (1954); Tokaty, *A History & Philosophy of Fluid Mechanics* (1971); Simón Calero, *La génesis de la mecánica de los fluidos* (1996); and Mikhailov, "The Origins of Hydraulics and Hydrodynamics in the work of the Petersburg Academicians" (1999).
88. Johann Bernoulli, "Hydraulica" (1742/1968). For the complete story of the development of the works by Daniel and Johann Bernoulli, see the preface by Hunter Rouse in Bernoulli, *Hydrodynamics by Daniel Bernoulli & Hydraulics by Johann Bernoulli* (1968).
89. See Truesdell, "Rational Fluid Mechanics (1687–1765)" (1954); and Rouse and Ince, *History of Hydraulics* (1957).
90. Clairaut, *Théorie de la figure de la terre* (1743).
91. Bouguer, "Comparaison des deux loix" (1734).
92. See Greenberg, *The Problem of the Earth's Shape from Newton to Clairaut* (1995), for a complete analysis of Bouguer's and Clairaut's work in the context of geodesy.
93. See Truesdell, "Rational Fluid Mechanics (1765–1788)" (1954); Tokaty, *A History & Philosophy of Fluid Mechanics* (1971); Simón Calero, *La génesis de la mecánica de los fluidos* (1996).
94. D'Alembert, *Traité de l'équilibre* (1744/1770).
95. D'Alembert, *Traité de dynamique* (1743/1758/1990).
96. D'Alembert, *Essai d'une nouvelle théorie de la résistance des fluides* (1752).
97. D'Alembert's aversion to experiments is described in Hankins, *Jean d'Alembert* (1970), especially pp. 3–4, 14–16.
98. D'Alembert's use of the word "pressure" was vague, often meaning "force"; the vector field he modeled using partial differentials was not for pressure but velocity. He divided resistance into three components: pressure, surface friction, and "tenacity" (the latter the resistance of the fluid to being split by a body); and he speculated on the possibility of negative pressure causing cavitation. Although these concepts sound quite modern, D'Alembert did not in fact go beyond a subjective description of the phenomena. See especially Truesdell, "Rational Fluid Mechanics (1765–1788)" (1954); and Simón Calero, *La génesis de la mecánica de los fluidos* (1996).
99. Euler, "Principia Motus Fluidorum" (1756/1757/1954).
100. Truesdell, "Rational Fluid Mechanics (1687–1765)" (1954), p. lxxxix.

101. Euler, “Continuation . . .” (1755), p. 316.
102. See Dugas, *A History of Mechanics* (1955/1988), pp. 333–349, for a description of Lagrange’s work.
103. Lagrange first described the stream function and velocity potential in a 1781 paper, “Mémoire sur la théorie du mouvement des fluides” (Memoir on the Theory of Movement of Fluids), and enlarged upon them in his 1788 *Mécanique analytique*.
104. See Tursini, “Leonardo da Vinci and the Problem of Navigation and Naval Design” (1953), pp. 97–98, for a description of Da Vinci’s experiments on three models of ships having different placements of the maximum section.
105. Rouse and Ince, *History of Hydraulics* (1957), pp. 113–122.
106. Baker, “Development of Hull Form of Merchant Vessels” (1938), pp. 53–54.
107. Wright, “Ship Hydrodynamics 1710–1880” (1983), pp. 27–28.
108. Ibid., pp. 28–29; Murray, *Treatise on Ship-building and Navigation* (1765), pp. 92–99.
109. Harley, “The Society of Arts’ Model Ship Trials, 1758–1763” (1991).
110. Hoving and Lemmers, *In tekening gebracht* (2001), pp. 102–103, 183–188.
111. Ibid., p. 103.
112. Chapman, *Tractat on skepps-byggeriet* (1775/1968), pp. 78–83. In his observation of Bird’s experiments as published by Mungo Murray, Chapman described (perhaps for the first time) the effects of blockage, noting that a body in a narrow channel tends to push the water level up ahead of it, so that the water descends to a lower level behind it.
113. Chapman, “Physiska rön” (1795); D. G. Harris, *F.H. Chapman* (1989), pp. 168–170.
114. A detailed description of the trials is given in D. G. Harris, *F.H. Chapman* (1989), pp. 171–179.
115. Chapman, *Försök till en theoretisk* (1806).
116. The parabola method is described in D. G. Harris, *F.H. Chapman* (1989), pp. 220–221. Tonello employed the parabola method from 1819 to 1849 (Marzari, “L’arte della progettazione e della costruzione navale a Trieste” [1997], pp. 184–186). Griffiths used the system in designing ocean steamers during the 1840s and 1850s (Griffiths, *Treatise on Marine and Naval Architecture* [1850], pp. 85–90). In the 1860s, while Nystrom was working in the U.S. navy, he unsuccessfully lobbied to introduce Chapman’s method for the construction of naval vessels. Nystrom, *A Treatise on Parabolic Construction of Ships* (1863).
117. Robins, *New Principles of Gunnery* (1742/1761). In 1745, at the behest of Friedrich II, Leonhard Euler translated this into German and provided extensive commentary on ballistics and its effects on cannon stress that greatly extended the theoretical basis of fluid mechanics and

strength of materials. An analysis of Robins's and Euler's impact on gunnery is given in Steele, "Muskets and Pendulums" (1994), and on rational fluid mechanics in Truesdell, "Rational Fluid Mechanics (1687–1765)" (1954).

118. Mascart, *La Vie et les travaux du Chevalier Jean-Charles de Borda* (1919), pp. 84–90; Taillemite, "Jean-Charles de Borda" (1999), p. 12.

119. Borda's skepticism of Newton may have been due to a 1748 letter from Benjamin Robins, shown to him by the French astronomer Pierre-Charles Le Monnier, in which Robins claimed to take no account of the (fluid shock) resistance theories used by Bouguer and others. Cited in Le Monnier, letter to Choiseul, folio 63 (21 January 1764).

120. Borda, "Expériences sur la résistance des fluides" (1763).

121. Borda, "Expériences sur la résistance des fluides" (1767), p. 503.

122. For a thorough analysis of Borda's memoirs, see Simón Calero, *La génesis de la mecánica de los fluidos* (1996), pp. 272–286.

123. Thévenard, "Expériences sur la résistance des fluides" (1800), pp. 33–50; Beauchesne, *Historique de la construction navale à Lorient* (1980), pp. 185, 187.

124. Planning of the basin began in March 1768; construction began in August; was interrupted by the rains in September; and recommenced in April 1769. The basin was finished a year after it was begun, in August 1769. Letters concerning the construction of the basin and the first few months of testing are in ANF Fonds Marine G 101. See also Henrat, *Innovations techniques dans la marine* (1990), pp. 150–151.

125. Thévenard, "Expériences sur la résistance des fluides" (1800), pp. 113–128; Montucla, *Histoire des mathématiques*, vol. 4 (1802/1968), pp. 442–448.

126. Several secondary sources indicate that a notice of Thévenard's work was published in either 1770 or 1772 in the *Journal des sçavans*, but I have not found it.

127. Bossut, D'Alembert, and Condorcet, *Nouvelles Expériences sur la résistance des fluides* (1777), p. 7.

128. Thévenard, *Mémoires relatifs à la marine* (1800).

129. One short memoir by the French navy ensign Jean-Jacques de Marguerie appeared in 1773, and in it he attempted to put forward a new theory of fluid resistance based on Thévenard's results. Marguerie, "Sur l'Établissement d'une nouvelle théorie de la résistance de fluides par l'expérience" (1773).

130. Bossut's textbook was *Traité élémentaire d'hydrodynamique* (1771). The Picardy Canal project is detailed in Redondi, "Along the waters: the genius and the theory (1985/1997)."

131. Bossut, D'Alembert, and Condorcet, *Nouvelles Expériences sur la résistance des fluides* (1777), p. 2.

132. Franklin, “Letter to Sir John Pringle 10 May 1768” (1769). Bossut and his colleagues read the letter in a 1773 French translation of Franklin’s complete works. Bossut, D’Alembert, and Condorcet, *Nouvelles Expériences sur la résistance des fluides* (1777), p. 8.

133. Chapman’s observations on blockage in his *Tractat on skepps-byggeriet* would not be published in French until 1781.

134. Bossut, and D’Alembert, and Condorcet, *Nouvelles Expériences sur la résistance des fluides* (1777), p. 193. The Picardy canal project was stopped for other reasons, but was restarted in 1805 under Napoleon with two smaller subterranean canals, and finished in 1810. The overall Saint Quentin canal system, as it is now known, is 41 kilometers long, but the longest underground section is only 5.6 kilometers.

135. From Bossut, D’Alembert, and Condorcet, *Nouvelles Expériences sur la résistance des fluides* (1777), pp. 153–176; Wright, “Ship Hydrodynamics 1710–1880” (1983), pp. 32–33; Simón Calero, *La génesis de la mecánica de los fluidos* (1996), pp. 294–305. Surprisingly few of D’Alembert’s theoretical contributions were visible in the report, which was dedicated mostly to the experimental setup and results.

136. Bossut, “Nouvelles Expériences sur la résistance des fluides” (1778), pp. 376–380; Simón Calero, *La génesis de la mecánica de los fluidos* (1996), pp. 305–307.

137. Bossut and Condorcet became something akin to hydraulic consultants of their day, being called upon to advise on other canal projects around France (Coste and Crépel, “Comment Imaginer un Mathématicien du XVIII^e siècle?” [1994], p. 46). Bossut also obtained the chair of hydrodynamics (for political reasons) at the Academy of Architecture, which he held for 15 years, until its abolition during the French Revolution. Hahn, “The Chair of Hydrodynamics in Paris” (1964).

138. Bossut, *Traité élémentaire d’hydrodynamique* (1771). Du Buat was probably unaware that in 1769 his civil counterpart, Antoine Chézy of the School of Bridges and Roadways, had completed an extensive study on the effects of canal cross section on discharge, which remained in the school archives until it was rediscovered in 1897; the relation of discharge to slope, cross section, and friction used by hydraulic engineers today is called the Chézy formula.

139. Dugas, *A History of Mechanics* (1955/1988), pp. 316–319; Rouse and Ince, *History of Hydraulics* (1957), pp. 129–134.

140. Pitot, “Description d’une machine pour mesurer la vitesse des eaux courantes, & le sillage des vaisseaux” (1732). It was not called a Pitot tube until it was perfected in the 1850s by the French engineer Henry Darcy.

141. Pitot proposed the device as a ship’s log to the minister of the navy in 1733, resulting in a flurry of back-and-forth memos with navy officers on its pros and cons (these memos are in ANF Fonds Marine G/100/2, folios 26–55. See Henrat, *Innovations techniques dans la marine* [1990], pp. 141–142). The obvious problem was that a set of tubes penetrating the hull was a potential source of flooding. The French constructor Alexandre Savérien proposed a solution to this problem by attaching a set of Pitot tubes to the stern of the ship (Savérien, *L’Art de mesurer sur mer le sillage du vaisseau* [1750], pp. 40–44). The system would not have worked in practice, since the rise and

fall of the stern would have constantly changed the pressure in the tubes, making the readings useless.

142. Du Buat, *Principes d'hydraulique* (1779), Volume 2, pp. 364–369; Dugas, *A History of Mechanics* (1955/1988), pp. 316–319; Rouse and Ince, *History of Hydraulics* (1957), pp. 132–134.

143. Du Buat, *Principes d'hydraulique* (1779), Volume 2, pp. 369–380.

144. One erroneous result of Du Buat's measurements was that the force of moving water on a stationary object was greater than the force needed to move the body through still water at the same speed, a condition known as "Du Buat's paradox."

145. Romme, *L'Art de la marine* (1787), pp. 41–85. Romme's account of his presentations before the Academy was repeated at length in Montucla, *Histoire des mathématiques* (1802/1968) vol. 4, pp. 453–459; and Fincham, *A History of Naval Architecture* (1851/1979), pp. xlix–lxix. An Academy prize on the subject of reconciling the differences in experimental and theoretical results for fluid resistance was declared for 1789 and 1791. The prize was eventually shared by Romme (who essentially reiterated his account from *L'Art de la marine*) and Friedrich Wilhelm Anton Gerlach, a philosophy professor at the Royal Engineering Academy in Vienna (who provided some theoretical principles). However, the French Revolution intervened and the Academy closed in 1793, so the prize entries were not published, and remain in manuscript form in the archives of the French Academy of Sciences. Crépel, "Les Travaux d'un savant, Charles Romme" (1996), pp. 301–302.

146. Brown, "The Speed of Sailing Warships, 1793–1840: An Examination of the evidence" (1990), pp. 187–192, and "The Form and Speed of Sailing Warships" (1998). For a complete explanation of ship resistance, see Lewis, *Principles of Naval Architecture* (1988), chapter 5, "Resistance," by J. D. van Manen and P. van Oossanen.

147. Brown, "The Speed of Sailing Warships, 1793–1840: An Examination of the Evidence" (1990), pp. 187–192.

148. Gardiner, *The Heavy Frigate* (1994), pp. 38–40. For an in-depth account of British "copying" of a French 74-gun ship, see Lavery, *Building the Wooden Walls* (1991).

149. From 1740 to 1800, the British navy captured 458,000 tonnes in foreign warships, while France, in second place, captured only 87,000 tonnes. Glete, *Navies and Nations* (1993), Volume 1, pp. 264, 272, 384.

150. Brown, "The Speed of Sailing Warships, 1793–1840: An Examination of the Evidence" (1990), pp. 156–159, 176–180.

151. Fincham, *A History of Naval Architecture* (1851/1979), pp. 255–275. It is interesting to note that the commission identified the principal cause for French inferiority of that era as thin and badly applied copper sheathing on the hulls, so that French hulls became rougher at a faster rate than did British hulls.

152. *Ibid.*, p. 260.

153. Cited in Le Monnier, letter to Choiseul, folio 63 (21 January 1764).

154. Murray, *Treatise on Ship-building and Navigation* (1765), supp., p. 3.
155. Quoted in Juan-García Aguado, *José Romero Fernández de Landa* (1998), pp. 110–111. The letter is also discussed in chapter 5.
156. Anonymous, “Consulta a varias personas . . . para aumentar la velocidad de la marcha” (1782).
157. Juan y Santacilia, *Examen marítimo* (1771/1992), vol. 2, pp. 112–132. A complete analysis is given in Simón Calero, “La mecánica de los fluidos en Jorge Juan” (2001), pp. 230–247.
158. Vial du Clairbois, *Encyclopédie méthodique: Marine* (1786/1987), vol. 2, pp. 340–355.
159. Euler, “Essai d’une théorie de la résistance qu’éprouve la proue d’un vaisseau dans son mouvement” (1778/1978); Truesdell, “Rational Fluid Mechanics (1687–1765)” (1955), p. lxxix. It is doubtful that either Euler or Du Buat knew of the other’s ideas on separation of resistance into components, given their near-simultaneous publication.
160. Ducrest, *Essais sur les machines hydrauliques* (1777), pp. 132–197.
161. Ducrest, *Nouvelle Theorie de la construction des vaisseaux* (1799).
162. Ducrest, *Notice de l’expérience faite à Copenhague* (1799). Ducrest had previous experience, having overseen the construction of the 32-gun frigate *Prosélyte* in 1785, although the ship turned out to be a disaster (Demerliac, *La Marine de Louis XVI* [1996], p. 67; Acerra, *Rocheport et la construction navale française* [1993], Volume 2 p. 390). Ducrest then constructed another vessel in Denmark, also a disaster, before developing his concept for *Svar-til-alt*, which was to build the hull of five layers of boards, three running horizontally and two vertically, and not to use any heavy frames to hold the hull together. Ducrest departed Denmark before the trials of the ship were complete, leaving Coninck to sort out the debts. Langen, “En fransk skibskonstruktør i Danmark” (2002).
163. Gay, *Mémoire sur la forme de la carène des vaisseaux* (1792), p. 12.
164. Accounts of Beaufoy’s experiments are given in Wright, “Ship Hydrodynamics 1710–1880” (1983), pp. 39–67, and “Mark Beaufoy’s Nautical and Hydraulic Experiments” (1989); and Schaffer, “Fish and Ships: Models in the Age of Reason” (2004). Brunel’s experiments on the *Archimedes’* propeller are cited in Brunel, *The Life of Isambard Kingdom Brunel* (1870/1971), pp. 546–547. Russell’s 1863 notes on resistance of the *Great Eastern* and the Holyhead packets used Beaufoy’s results for planar resistance. Russell, notebook 6, 19 June 1863, nonpaginated.
165. Wright, “Ship Hydrodynamics 1710–1880” (1983), pp. 89–90.
166. Emerson, “The Construction of the Fore Part of a Ship That Will Move Through the Water with the Least Possible Resistance” (1800). *Doctrine of Fluxions* was published several times between 1743 and 1768.
167. Hällström, “Försök till en avhandling om solidum minime resistance” (1808). He also referred to Euler’s work in developing stability equations based on the “moment of stiffness” (discussed in chapter 5). Nordmark’s theory on fluid resistance received a prize from the Russian

imperial navy. Nordmark, “Grundformler till en ny teori om flytande kroppars motståend” (1805/1808).

168. Cayley, “On Aerial Navigation” (1810).

169. A full account of John Scott Russell’s solid of least resistance is given in Wright, “Ship Hydrodynamics 1710–1880” (1983), pp. 68–81.

170. Jefferson, “Description of a Mould-board of Least Resistance” (1799); Cohen, *Science and the Founding Fathers* (1995), pp. 293–294.

171. My italics. This famous “head and heart letter” is openly cited in many sources, such as Jefferson, *Political Writings* (1999), pp. 10–18.

Chapter 4: Inventing the Metacenter

1. For brief accounts of *Lune* and the expedition to Djidjelli, see Vergé-Franceschi, *Chronique maritime de la France d’ancien régime* (1998), pp. 410–411; and Turcat, “La Tragique Histoire de la *Lune*” (1999). The wreck of *Lune* was discovered quite by accident on 15 May 1993, by Paul-Henri Nargeolet of IFREMER (Institut Français de Recherche pour l’Exploitation de la Mer [French Research Institute for the Exploitation of the Sea]), during a dive on the submersible *Nautilus* (IFREMER press release (19 November 1993). I thank Paul-Henri Nargeolet for this information. For accounts of the wreck and subsequent discovery, see Grousset, “On a plongé sur la *Lune*” (1994), and “Naufrage de la *Lune*” (2000).

2. Hoste, *Théorie de la construction des vaisseaux* (1697), p. 46. In addition to misrepresenting the cause of the wreck, Hoste was wrong about the date (he gave 1678 instead of 1664) and location (he said Îles d’Hyères instead of Toulon).

3. Mary Rose Trust Web site, accessed July 2000.

4. Vasa Museum Web site, accessed July 2000; Ohrelius, *Vasa, the King’s Ship* (1962), pp. 14–37. The stability test is discussed later in this chapter.

5. Fred Hocker of the Statens Maritima Museer (National Maritime Museums) in Stockholm is currently (as of this writing, January 2006) leading an investigation into the reasons for the capsizing of *Vasa*, based on a critical reexamination of the evidence. Thanks to Fred Hocker, Olof Pipping, and Jan Glete for this information.

6. Rodger, *The Wooden World* (1986), pp. 46–54.

7. See Hepper, *British Warship Losses in the Age of Sail* (1994).

8. J. E. Harris, “Copper and Shipping in the Eighteenth Century” (1992), pp. 180–181.

9. See Sobel, *Longitude* (1995), for a popular account of this prize.

10. Kalmar Läns Museum Web site, accessed March 2002. My thanks to Lars Einarsson, marine archaeological director of the Kalmar Läns Museum, for further details.

11. Abell, *The Shipwright’s Trade* (1948/1962), p. 31.

12. Hoste, *Théorie de la construction des vaisseaux* (1697), p. 46.
13. Bouguer, letter to Maurepas (1727); Bouguer, Letter to Maurepas (1730).
14. I owe many thanks to Horst Nowacki, Richard Barker, Jobst Lessenich, and Carla Rahn Phillips for guiding me through the minefield of the development of tonnage rules, which is an extraordinarily complex topic worthy of a separate Ph.D. thesis. All interpretations are mine alone.
15. Cicero, around 60 B.C., referred to ships by the number of amphora they carried (Gille, “Jauge et tonnage des navires” [1957], p. 89). The same principle is used today for container ships; cargo capacity is stated in terms of the number of 20-foot (6-meter) containers that can be carried, called twenty-foot equivalent units or TEUs, even though most containers are now 40 or even 55 feet long (12 to 16 meters).
16. The “Kepler barrel problem” began as Kepler’s attempt to determine the volume of wine barrels, and led to his developing a series of equations to determine the volume of conic solids that brought him close to inventing the calculus.
17. This corresponds to 913 liters, and when it is filled with seawater, it weighs about 1,014 kilograms (2,240 pounds), from whence the “long ton” originates.
18. For an account of the problems in establishing equivalent units of volume and weight for cargo, and of fraudulent practices, see Burwash, *English Merchant Shipping* (1947), pp. 89–93.
19. Lane, *Venetian Ships and Shipbuilders of the Renaissance* (1934), pp. 246–249.
20. Salisbury, “Early Tonnage Measurement in England” (1966), pp. 45–46; Barker, “Fragments from the Pepysian Library” (1986), p. 176; Johnston, *Making Mathematical PRACTICE* (1994), p. 132.
21. Salisbury, “Early Tonnage Measurement in England” (1966), p. 49.
22. The 1694 act was repealed two years later, but a similar rule was instated in 1720 that would last another 100 years. Driel, *Tonnage Measurement* (1925), pp. 10–12.
23. Phillips, *Six Galleons for the King of Spain* (1986), pp. 60–61, 228–229; Laughton, “English and Spanish Tonnage in 1588” (1958), p. 152; Rubio Serrano, “Métodos de arqueo en el siglo XVI” (1989), and *Arquitectura de las naos y galeones de las flotas de Indias*, vol. 1 (1991), pp. 165–175.
24. Crescentio, *Nautica Mediterranea* (1602), pp. 168–169.
25. Šišević, “Računanje obujma broda u Dubrovniku” (1952); Zagreb University Web site, *Centuries of Natural Science in Croatia*, accessed December 2000; Barker, *Ragusan Shipbuilding in the Mid-sixteenth Century*, accessed March 2002.
26. Pezenas, *La Théorie et la pratique du jaugeage* (1773), p. 33.
27. For example, Moitoret de Blainville, *Traité du jauge* (1698); Barthès de Marmorières, *Mémoires d’agriculture et de mécanique* (1762); and Pezenas, *La Théorie et la pratique du jaugeage* (1773).
28. A complete account of the development of tonnage in Britain can be found in a series of articles by William Salisbury: the tonnage measurement series in *Mariner’s Mirror* (1966–1968).

Two other excellent general sources are Driel, *Tonnage Measurement* (1925); and Morineau, *Jauge et méthodes de jauge* (1966).

29. Lane, “Venetian Maritime Law” (1962), pp. 34–35.

30. Attoma-Pepe, “Un Aperçu du franc-bord des navires au moyen age” (1976), p. 13.

31. Most of Mathew Baker’s hull elevations in his manuscript “Fragments of Ancient English Shipwrightry” mark the “swimming line,” though there is no text or calculation to support it. My thanks to the water engineer Richard Barker for noting this.

32. “In air, for instance, a talent’s weight of wood is heavier than a minima of lead, but in water the wood is lighter . . . the reason why broad things keep their place is because they cover so wide a surface and the greater quantity is less easily disrupted. Bodies of the opposite shape sink down because they occupy so little of the surface, which is therefore easily parted.” Aristotle, “On the Heavens,” in his *Complete Works* (1984), vol. 1, pp. 402–405.

33. A complete translation and setting in context of this discussion is provided in Drake, *Cause, Experiment, and Science* (1981).

34. Fournier, *Hydrographie* (1643/1667/1973), pp. 608–609. His solution to the problem of calculating displacement was to fill the ship with water measured in barrels (pp. 612–614), an idea also described by Witsen. Witsen, *Aeloude en hedendaegsche scheeps-bouw en bestier* (1671), pp. 317–318.

35. There are no contemporary accounts to support this; the earliest citations date only from about 1800 (e.g., Charnock, *A History of Marine Architecture*, vol. 2 [1800], p. 26). The British constructor James Baker is also given credit for developing the idea for use on the *Henry Grace à Dieu*, or *Great Harry*, in 1514. Howarth, *The Men-of-War* (1978), p. 21.

36. Friel, “The Carrack” (1994), p. 89.

37. Pett, *The Autobiography of Phineas Pett* (1918), pp. xcii–xcv.

38. Harris, *Trinity House of Deptford Transactions* (1983), pp. 135, 142. The son Peter Pett at Woolwich estimated the draft of *Leopard* at 3.9 meters; it was measured after fitting out at 4.1 meters. The nephew Peter Pett at Deptford estimated that *Swallow* would draw 3.7 meters; it was measured at 3.9 meters. In both cases the drafts were specifically positioned to provide a freeboard to the gun ports of 1.75 meters. I thank the maritime historian Brad Loewen for alerting me to this passage.

39. Pepys, *Naval Minutes*, vol. 60 (1926), p. 241. The narration is retrospective; Deane was actually knighted in 1673.

40. Croissy, “Mémoire sur la marine d’Angleterre” (1672/1689).

41. Dean, *Deane’s Doctrine of Naval Architecture* (1670/1981), pp. 7–20.

42. Samuel Pepys’s diary entry for 19 May 1666, in connection with the 60-gun *Rupert*: “And then he [Deane] fell to explain to me the manner of casting the draught of water which a ship will draw before-hand—which is a secret the King and all admire in him; and he is the first that

hath come to any certainty before-hand of foretelling the draught of water of a ship, before she is launched.” Pepys, *The Diary of Samuel Pepys* (1972), vol. 7, p. 121.

43. Deane, *Deane's Doctrine of Naval Architecture* (1670/1981), p. 71.

44. *Ibid.*, pp. 71–73.

45. These were explicitly shown in Deane's manuscript “Method of Measuring the Body of a Ship and Pre-calculating Her Draught” (undated, ca. 1670).

46. Deane, *Deane's Doctrine of Naval Architecture* (1670/1981), p. 73.

47. Fitzmaurice, *Life of Sir William Petty* (1895), pp. 266–268. William Petty, although a doctor and an economist, built several experimental catamarans during his career. I thank the water engineer Richard Barker for alerting me to this passage.

48. Bjerg and Erichsen, *Danske orlogsskibbe* (1980), p. 16.

49. Orlogsmuseet Web site, *Online Archives*, accessed September 2003; Nielsen, *Major Danish Warships Built at the Holmen Shipyard 1692–1744*, accessed September 2003. It is possible that calculations of draft and displacement began much earlier in Denmark. The 1623 contract given to David Balfour to construct the 22-gun *Hummeren* called for a draft of 2.75 meters when completed (Bellamy: “David Balfour: Early Modern Danish Ship Design” [2006], p. 13).

50. My thanks to the naval historians Jakob Seerup and Mogens Anthon for this information.

51. Bourne, *Treasure for Travelers* (1578/1979), book 4, pp. 2–22; transcription on Richard Barker Web site, accessed March 2002. Bourne also described a second method derived from his teacher, the British mathematician John Dee, who had suggested a way of doubling or tripling a solid body, including “any mold or model of a ship,” using Archimedes' principle (Dee, *The Mathematicall Praeface* [1570/1975], facsimile pages “Statick”). Bourne's idea was to make a hollow scale model of the ship, fill it with water, weigh it, and then scale up the measurement. Bourne, an innkeeper at Gravesend, was a popularizer of science and inventions, not really an inventor himself, so his detailed descriptions of the link engine may indicate the use of displacement calculations in salvage operations within the Thames estuary, if not on a more widespread basis.

52. Driel, *Tonnage Measurement* (1925), pp. 44–45; Morineau, *Jauge et méthodes de jauge* (1966), pp. 92–93; Cerulus, “Un Mathématicien mesure les navires” (2001).

53. Bushnell, *The Complete Shipwright* (1664), p. 42.

54. Varignon's proposal gave the volume of a semi-ellipsoid as $11/21 \times (\text{length} \times \text{beam} \times \text{depth})$, a method that, while certainly easy to use, was rather inexact since it did not take into account the variations in hull form of different ships (Varignon, “Jaugeage d'un navire ellipsoïde,” *HMAS* [1721]). This figure $11/21$ (≈ 0.52) may be considered the first attempt at developing a “block coefficient” for ships, one cited later by Bouguer in his *Traité du navire* (pp. 253–254).

55. Bouguer claimed that Hocquart learned the technique from the Brest hydrographer Guillaume Coubard, who had employed the method from the 1680s (Bouguer, *Traité du navire* [1746],

p. 241). In fact, the “method of trapezoids” was known far earlier as a means of estimating the area under a curve.

56. The complete story of the Academy’s study of admeasurement is given in the following memoirs: Fontennelle, “Sur le Jaugeage des vaisseaux,” *HMAS* [1721]; Mairan, “Remarques sur le jaugeage des navires,” *HMAS* (1721); Varignon, “Jaugeage d’un navire ellipsoïde,” *HMAS* (1721); Bouguer, “Sur le Jaugeage des vaisseaux,” *HMAS* (1722); Mairan, “Instruction abrégée et méthode pour le jaugeage des navires,” *HMAS* (1724). Bouguer’s introduction to Reyneau and Bignon is discussed in Fauque, “Du Bon Usage de l’éloge: Cas de celui de Pierre Bouguer” (2001), pp. 364–365.

57. Bouguer, “De la mâturation des vaisseaux” (1727), pp. 24–25, and *Traité du navire* (1746), pp. 240–243.

58. Ollivier, *Traité de construction 1736* (1992), pp. 1–5, 382–387.

59. Boudriot, *Les Vaisseaux 50 & 64 canons* (1994), p. 151.

60. Vérin, “Un ‘Document technographique’: Le devis” (1987), and *La Gloire des ingénieurs* (1993), pp. 227–241.

61. Quoted in Vérin, *La Gloire des ingénieurs* (1993), p. 230.

62. La Croix, letter to Maurepas (25 March 1732). The problem with *Lys* was that the forward gun ports were too close to the waterline. Maurepas asked Blaise Ollivier investigate the problem; in an extraordinarily detailed 53-page memo, Ollivier explained that the problem was due to the ship hogging, and that the solution was to raise the forward half of the deck about 15 centimeters and lower the aft half by the same amount in order to keep the center of gravity the same, so as not to affect sailing qualities. Ollivier, letter to Maurepas (1732).

63. Bouguer, *Traité du navire* (1746), pp. 275–276. In his experiments on the metacenter (also around 1732) using the *Gazelle*, Bouguer accounted for the weight of each part of the ship, including the frames, planking, nails, masts, ropes, and pulleys. He also measured the center of gravity of each piece, using the keel as the reference point, and summed the moments to obtain the overall center of gravity.

64. This subsection is derived from Nowacki, “Archimedes and Ship Stability” (2001/2002); and Nowacki and Ferreiro, “Historical Roots of the Theory of Hydrostatic Stability of Ships” (2003).

65. Stevin’s book *Beghinselen des waterwichts* (Elements of Hydrostatics), published in 1586, is considered by historians to be the next important step, after Archimedes’ *On Floating Bodies*, toward the systematization of hydrostatics (Stevin, *The Principal Works of Simon Stevin*, vol. 1 [1955], p. 18). Stevin showed that the pressure exerted by a liquid on a surface depends on the height of the liquid and the area of the surface, independent of the volume of liquid. Pascal came to the same conclusions in his *Traité de l’équilibre des liqueurs* (Treatise on the Equilibrium of Liquids), published posthumously in 1663.

66. “Cortybegryp der vlietende topfvvaerheyt (Argument of the floating top-heaviness),” published in 1608. Stevin, *The Principal Works of Simon Stevin*, vol. 1 (1955), pp. 570–573.

67. Indeed, at the end of the proof, Stevin acknowledged that it would be “too difficult to find the centers of gravity of the many varied materials that are usually present in a ship,” so although he could not fulfill his original intent of establishing a theoretical analysis of top-heaviness, he claimed his theorem “may be of use to the man who should make an attempt to find it.”

68. Huygens, “De Iis Quae Liquido Supernatant Libri Tres” (1650/1908); Nowacki and Ferreiro, “Historical Roots of the Theory of Hydrostatic Stability of Ships” (2003), p. 6.

69. Parent, *Éléments de mécanique et de physique* (1700), pp. 200–239.

70. Hoste, *Théorie de la construction des vaisseaux* (1697), p. 48.

71. Hoste used this explanation to state that doubling a ship improves stability by raising the center of gravity. It is a surprising conclusion for Hoste to have reached, even for the era, since it was already well known that too much top weight would degrade a ship’s sailing performance.

72. Hoste, *Théorie de la construction des vaisseaux* (1697), pp. 49, 54.

73. *Ibid.*, pp. 55–59.

74. Sheldon, “Om skeppens tyngd och rymd uti watnet” (1741), and “Om center gravitatis uti ot skepp” (1742); Polhem, “Ny method at pröfva lasten i et skep” (1743). These were written just before Bouguer’s *Traité du navire* was published (1746), which rendered Hoste’s ideas—and therefore those of Sheldon and Polhem—immediately obsolete.

75. Euler, “Meditationes Super Problemate Nautico” (1727/1728/1974).

76. Bouguer, “De la mâtüre des vaisseaux” (1727/1728), pp. 24–25.

77. Camus, “De la mâtüre des vaisseaux” (1727/1728), pp. 51–61. Camus, however, erred in suggesting that this proportionality be based on length to the fourth power, incorrectly assuming that displacement is proportional to length cubed.

78. I thank Horst Nowacki for this insight.

79. For biographical information on Maurepas, see Condorcet, “Éloge de M. le comte de Maurepas” (1781); Fillion, *Maurepas, ministre de Louis XV* (1967); Lamontagne, *Ministère de la marine, Maurepas et Pellerin* (1972); Bourland, *Maurepas and His Administration of the French Navy* (1978); Maurepas and Boulant, *Les ministres et les ministères du siècle des lumieres* (1996), pp. 283–289; and Picciola, *Le Comte de Maurepas* (1999).

80. The Maurepas Collection at Cornell University contains extensive correspondence among Maurepas, Ollivier, and Coulomb, often in the form of lengthy and highly detailed reports of scientific experiments or shipbuilding practices. Maurepas, in his responses, showed both a good grasp of the issues and a shrewd appreciation of character, frequently insisting that his constructors evaluate each others’ reports.

81. La Croix, “Mémoire sur la nécessité de pourvoir à la disette et à la foiblesse des ouvriers” (1719/1996); Picciola, *Le Comte de Maurepas* (1999), p. 159. Letters regarding La Croix’s longitude experiments are in ANF Fonds Marine G 91. Henrat, *Innovations techniques dans la marine* (1990), pp. 51–52.

82. I am deeply indebted to Horst Nowacki, who developed the systematic methodology of analysis used in the following sections.

83. Cooper, *Catalogue of the Scott Collection* (1954), p. 160. “Parallèle des vaisseaux” was item 804 in the Royal Institution of Naval Architects (RINA) Scott collection. Little is known about the manuscript, other than the description in the Scott collection catalog, and an allusion to it by La Croix in a letter to Maurepas regarding the problems of *Lys* mentioned earlier (La Croix, letter to Maurepas [1732]). RINA sold the manuscript at a Christie’s auction (lot 94, on 11 November 1999); a Paris book dealer bought it; and it was then resold to a private owner. All my attempts to contact the new owner have been rebuffed. Locating it could provide important clues as to the role of Maurepas in the development of stability theory.

84. The following analysis uses as a basis the Knowles translation of La Croix’s book, *Abstract on the Mechanism of the Motion of Floating Bodies* (1746/1775), as described in note 86. I am indebted to Horst Nowacki for his assistance in this analysis.

85. Grandjean de Fouchy, “Examination of proposal of M. de La Croix” (1735).

86. La Croix, “Extrait du mécanisme des mouvemens des corps flottants” (1735), and “Éclaircissements . . .” (1736). The two very small books were published by Chaubert, normally a poetry house, and Charles Robustel, a publisher of ecclesiastical texts. Given their tiny sizes and small press runs, they may have been paid for by La Croix himself. The British naval officer Charles Knowles translated the work into English ten years later as *Abstract on the Mechanism of the Motion of Floating Bodies* (1746/1775). He said it “contains more knowledge in the art of ship-building than any book hitherto published” and claimed it agreed with his observations while he built ships in southern Russia (1770–1774), even though Euler, whom he knew personally, would have pointed out La Croix’s errors to him.

87. It is not clear whether Maurepas, perhaps displeased with La Croix’s work on navigation and stability, effectively exiled him; he was certainly unhappy with La Croix’s performance in Martinique, and apparently did not respond to his entreaties to be promoted. La Croix, letter to Maurepas, 1747.

88. Euler, “Judicium de Libello Domini de La Croix” (1735/1967), and “Notae ad Responsiones” (1736/1967).

89. This analysis of Euler’s methodology, entirely the work of Horst Nowacki, is from Nowacki and Ferreiro, “Historical Roots of the Theory of Hydrostatic Stability of Ships” (2003), pp. 14–20. Original source material is Euler, *Scientia Navalis* (1749/1967/1972), vol. 1, pp. 3–166, and vol. 2, pp. 42–130.

90. Truesdell, “Rational Fluid Mechanics, 1687–1765” (1954), p. xvii.

91. Demerliac, *La Marine de Louis XV: Nomenclature des navires français de 1715 à 1774* (1995), p. 68.

92. This subsection is from Nowacki and Ferreiro, “Historical Roots of the Theory of Hydrostatic Stability of Ships” (2003), pp. 10–14. A detailed examination of the mathematics of the metacenter is also given in Dhombres, “Mettre la Géométrie en crédit” (1999).

93. Bouguer, *Traité du navire* (1746), pp. 199–324.

94. *Ibid.*, pp. 256–257.

95. *Ibid.*, pp. 280–282. Bouguer stated that he calculated the metacenter of *Gazelle* while it was still unloaded, but that he “did not believe [it] was worth the trouble to verify, in seeking the placement of the metacenter exactly,” as he knew it would change with the addition of ballast. Instead, he later described the inclining of an 1,800-tonne vessel, not *Gazelle*, which was heeled by hanging a 5-tonne weight over the side, the measurements giving him a GM of 1.4 meters. However, it is not at all certain that this experiment took place. *Ibid.*, p. 321.

96. For further reading on “multiples,” see Merton, *The Sociology of Science* (1973); Brannigan, *The Social Basis of Scientific Discoveries* (1981); and Zuckerman, “The Sociology of Science” (1988).

97. Euler, *Scientia Navalis* (1749/1967), vol. 1, p. 15.

98. Derived from Nowacki and Ferreiro, “Historical Roots of the Theory of Hydrostatic Stability of Ships” (2003), p. 23. I am indebted to Horst Nowacki for the idea of this rigorous comparison.

99. The contrast between the stability equations of Bouguer and Euler is brought out in Montucla, *Histoire des mathématiques*, vol. 4 (1802/1968), p. 389; and Dhombres, “Mettre la Géométrie en crédit” (1999), pp. 335–336.

100. Sources of plans and information for table 4.2: **France**—Villiers, *La Marine de Louis XVI* (1985); Boudriot, *Les vaisseaux 50 & 64 canons* (1994), and *Les Vaisseaux 74 à 120 canons* (1995). **Spain**—I thank José María de Juan-García Aguado, who examined plans at the Museo Navale (Naval Museum), Madrid. Other information is from Juan-García Aguado, *José Romero Fernández de Landa* (1998). **Denmark**—I thank Jakob Seerup, who examined plans at the Orlogsmuseet, Copenhagen. **Sweden**—Thanks to Olof Pipping, who examined the Marinens ritningar Serie A I—Linjeskepp (Drawings of the Navy, Series A I—Ships of the Line) at the Krigsarkivet (War archives), Stockholm. Other information is from D. G. Harris, *F.H. Chapman* (1989). **Britain**—My gratitude to John Hootman, who examined the Ships’ Draughts at the Caird Library, National Maritime Museum, Greenwich. **Netherlands**—Hoving and Lemmers, *In tekening gebracht* (2001). **Venice**—Penzo, *Navi Veneziane/Venetian Ships* (2000). Note: “tonnes per cm” is the modern expression for specific immersion (at the time called “solidity”), which was given in each country’s units (e.g., tonnes per *pouce* in France, tonnes per *fod* in Denmark, etc.).

101. Choiseul, *Ordonnance du roi* (1765); Villiers, *La Marine de Louis XVI* (1985), p. 13.

102. A collection of manuscripts from Duhamel du Monceau’s estate at the Phillips Library, Peabody-Essex Museum, Salem, Mass. (MH25), contains many examples of detailed stability calculations submitted by constructors during the 1760s–1770s, as well as instructions on how to calculate centers of gravity and volume.

103. For example, an unpublished manuscript by the Rochefort constructor Pierre Morineau provides 12 detailed pages of weights for ships of various rates, including frames, planking, caulking, nails, munitions, and masts. Morineau, *Repertoire de construction* (1752).

104. These methods—calculating weights using dimensional ratios from parent ships and using weight breakdowns by functional group—are surprisingly similar to those used by naval architects today; see, for example, SAWE, *Weight Control Technical Requirements for Surface Ships* (1997).

105. The following is from Villiers, *La Marine de Louis XVI* (1985), pp. 148–150.

106. Chevillard and Clairin-Deslauriers, letter to Duhamel du Monceau (1765).

107. Villiers, *Marine royale, corsairs et trafic* (1991), pp. 695–697; and Boudriot, “Constructeurs et constructions navales à Rochefort” (1985), pp. 20–22. The “unpardonable error” quote was from a young ensign named Viella aboard the *Pluton*, so his criticism should be taken with a grain of salt. Clairin-Deslauriers had been Duhamel du Monceau’s first student in 1741 and had had a reasonably successful career. Antoine Grognard, who had been junior to Clairin-Deslauriers but was now engineer general of the navy, was called in to rectify the situation. He was left in the uncomfortable position of defending his former mentor’s calculations, claiming that the framing was not seasoned (i.e., left to dry), and thus was heavier with sap. Grognard’s own calculations, however, were also suspect; his estimate of 7 *pouces* (about 20 centimeters) for the $\overline{GM}$ of *Scipion* was clearly wrong, as it would have rolled right over in the slightest puff of wind. Ships of that size typically had a $\overline{GM}$ of around 1.0–1.5 meters.

108. Romme, *L’Art de la marine* (1787), pp. 106–112. The experiments were quoted verbatim in other books, such as, Steel, *Elements and Practice of Naval Architecture* (1805/1977), pp. 138–140. The experiments compared *Scipion* and its sisters with better-performing 74s such as *Magnifique* and *Sceptre*, which had similar dimensions. Romme noted that the problem with *Scipion* (apart from a faulty weight estimate) was that the hull narrowed more quickly fore-and-aft (i.e., it had a smaller water plane moment of inertia) than the other 74s. The doubling of the hulls had the desired effect, and *Scipion*, *Pluton*, and *Hercule* all went on to fight in the battle of the Chesapeake, which helped bring the War of the American Independence to a close.

109. Vice Admiral Klas Fleming, in charge of construction, had witnessed a stability test performed on *Vasa* prior to its maiden voyage. Thirty men had run back and forth across the *Vasa*’s deck when it was moored at the quay. The men had to stop after three runs, well before the test could be completed—otherwise, the ship would have capsized. Ohrelius, *Vasa, the King’s Ship* (1962), p. 24.

110. Boudriot, *The Seventy-four Gun Ship* (1986), pp. 31–32. My thanks to Jean Boudriot for additional, clarifying information on Borda’s rule.

111. Although he was only 26 years old and recently graduated from Duhamel du Monceau’s “Little Navy School,” Clairin-Deslauriers’ idea caught the interest of two senior officers at the Brest dockyard, Sébastien Bigot de Morogues and Paul Ozée Bidé de Chézac, who provided the material support that allowed him to proceed with his experiment. He also enlisted the help of his friend Grognard, and received advice from Bouguer on how to conduct the inclining; he then reported the results back to his former teacher Duhamel du Monceau. Clairin-Deslauriers, letter to Duhamel du Monceau (1748).

112. Le Monnier, letters to Choiseul (1763–1764).

113. Quoted in Juan-García Aguado, *José Romero Fernández de Landa* (1998), pp. 110–111.

114. Sheldon, “Om skeppens tyngd och rymd uti Watnet” (1741), and “Om center gravitatis uti ot skepp” (1742); D. G. Harris, *F.H. Chapman* (1989), p. 18.

115. My thanks to Jan Glete for this information on Sohlberg.

116. Some sources place Simpson’s tutelage of private students such as Chapman in London coffeehouses, which were popular venues for gatherings and even lectures in that era; but the story, though plausible, may be apocryphal.

117. Simpson, *Mathematical Dissertations* (1743). Simpson never actually claimed to have invented the rule; it was first expressed by the British mathematician James Gregory in his 1668 *Geometriae Pars Universalis* (Universal Geometry) and was well known by Simpson’s time.

118. Chapman bought Bouguer’s *Traité du navire* and Euler’s *Scientia Navalis*. He (evidently) did not have Duhamel du Monceau’s *Éléments*, but did have Mungo Murray’s English translation, *A Treatise on Shipbuilding*. Bruzelius, *Maritime History Virtual Archives*, Chapman’s biography, accessed February 2003.

119. Chapman’s first known use of this formula was in a 1767 worksheet for a 70-gun ship, reproduced in D. G. Harris, *F.H. Chapman* (1989), pp. 215–220.

120. Much of Chapman’s support came from his close connections with the militaristic “Hats” party, which engaged in a back-and-forth struggle for dominance with the more nonviolent “Caps” party. Chapman also had the ear of King Gustavus III, who shared his views on strategy and technology. Sheldon, by contrast, was a typical constructor who had spent his life in the Karlskrona dockyard and had developed no political connections, and thus had no supporters to rival those of Chapman. My gratitude to the Swedish naval historians Olof Pipping and Jan Glete for these observations.

121. Murray, *Treatise on Ship-building and Navigation* (1754).

122. For example, the appendix of John Fincham’s *A History of Naval Architecture* (1851/1979), pp. 400–415, has lists of ships from many nations circa 1830–1850. Those of France, Sweden, Denmark, and Russia show stability details such as displacement, center of buoyancy, and metacenter; but the list for British ships shows only admeasurement tonnage.

123. Harley, “The Society of Arts’ Model Ship Trials, 1758–1763” (1991), pp. 62–63.

124. Anonymous, “Remarks on the Forms and Properties of Ships” (1800). The author may have been one of the founders of the Society, Sir John Borlase Warren, at that time a naval captain and probably the officer responsible for carrying out the experiments (Brown, *Before the Ironclad* [1990], p. 16, and “How It All Began” [1991], p. 5). The author says that the experiments were ordered by the “late” Admiral Leveson-Gower, almost certainly referring to John Leveson-Gower, who was rear admiral from 1787 to 1790 and died in 1792 (Clowes, *The Royal Navy: A History* [1898/1996], vol. 3, p. 567). These inclinations were widely reported. See, e.g., Steel, *The Elements and Practice of Naval Architecture* (1805/1977), pp. 140–141.

125. Hoving and Lemmers, *In tekening gebracht* (2001), pp. 131–132.
126. Penzo, *Navi Veneziane/Venetian Ships* (2000), pp. 36–37. Poleni may have also performed stability calculations, but I have seen none to date.
127. Zanelli, “La scuola di ‘naval architettura’ nell’Arsenale di Venezia” (1997).
128. Paul Hoste, in his 1697 *Théorie de la construction des vaisseaux*, addressed roll and pitch in qualitative terms—claiming, for example, that the center of gravity should be as far aft as possible in order to reduce pitch (p. 71), and that the center of buoyancy should be as high as possible to reduce rolling (p. 82).
129. Daniel Bernoulli, “Commentationes de Statu Aequilibrîi” (1738).
130. Daniel Bernoulli, “De Motibus Oscillatoriis” (1739).
131. *Ibid.*, p. 106.
132. For a complete explanation of Daniel Bernoulli’s first memoirs, see Bertin, “Notes on Waves and Rolling; Historical Introduction: Essay on Daniel Bernoulli” (1873); and Cerulus, “Comments on Daniel Bernoulli and Floating Bodies” (to appear). I am grateful to Dr. Cerulus for providing me with preprints of his lucid commentary, from which my analysis was principally derived.
133. In a 1751 letter, Bouguer told Bernoulli that he had just read his memoir on stability and that “I could only congratulate myself that my results are so perfectly in accord with yours.” Quoted in Cerulus, “Comments on *Principes Hydrostatiques et Mécaniques*” (2004).
134. Bouguer, *Traité du navire* (1746), p. 332.
135. *Ibid.*, pp. 325–346.
136. Bouguer, “Mémoire sur le mouvement d’oscillation des corps qui flottent” (1755).
137. Bouguer, *De la Manoeuvre des vaisseaux* (1757), pp. 220–274.
138. Euler, *Scientia Navalis* (1749/1972), vol. 2, pp. 149–203.
139. Euler, *Théorie complete de la construction et de la manœuvre des vaisseaux* (1773/1978), p. 97.
140. D’Alembert, *Essai d’une nouvelle théorie de la résistance des fluides* (1752), pp. 143–162.
141. Chauchot, *Sur les Mouvemens de roulis et tangage des navires* (1755); Groignard, “Mémoire” (1755/1759).
142. It is of particular interest to note Chauchot’s recommendation of false keels for roll damping. Bernoulli, Bouguer, and Euler all explicitly stated in their works that they had neglected the effects of the resistance of the water, arguing that it would be “negligible.” In fact, all three measures proposed by Chauchot are employed today: hull flare provides a greater righting moment at large angles of heel, which reduces the roll angle; container and passenger vessels are generally designed with as small a $\overline{GM}$ as possible to diminish roll acceleration; and bilge keels are universally used as roll-damping devices.

143. Chauchot's prize entry was published independently, and did not appear in the *Recueils des pieces qui ont remporté les prix* (Collection of Works That Have Taken the Prizes). Chauchot (his first name is not recorded) died at sea on the 74-gun *Palmier* on 10 June 1755, during an engagement with a British squadron off Canada. Chauchot, personal dossier, no date.

144. Bouguer found Chauchot's entry "full of geometrical faults but at the same time full of good ideas," and succeeded in having the subject reexamined. He exhorted Leonhard Euler several times to enter the competition, which Euler finally did for the 1759 prize, after Bouguer's death. Bouguer, "Lettres de Bouguer à Euler" (1966), letters of 19 November 1754 and 1 May 1755, pp. 241–243.

145. Cerulus, "Comments on Daniel Bernoulli and Floating Bodies" (to appear).

146. Daniel Bernoulli, "Principes hydrostatiques et mécaniques" (1757). Once again, Bernoulli's work suffered a delay in publication, in this case 14 years (1771).

147. Although Bernoulli did not address resonance damping in a theoretical way, he did recommend (as did Chauchot) the use of false keels.

148. For example, mathematical models of waves were developed by George Stokes in the 1840s, and the distribution of wave pressure on the hull would again be identified by W. E. Smith in 1883.

149. For a complete explanation of Daniel Bernoulli's Academy prize memoir, see Cerulus, "Comments on *Principes Hydrostatiques et Mécaniques*" (2004). I am grateful to Dr. Cerulus for providing me preprints of his lucid commentary, from which my analysis was principally derived. Other analyses of Bernoulli's prize memoir are given in Montucla, *Histoire des mathématiques*, vol. 4 (1802/1968), p. 469; and Fincham, *A History of Naval Architecture* (1851/1979), pp. xxvii–xxx.

150. Euler, *Mémoire* (1759); Grognard, *Mémoire* (1755/1759).

151. Euler, *Examen des efforts qu'ont à soutenir toutes les parties d'un vaisseau* (1759).

152. Grognard, "Mémoire" (1755/1759). Grognard had developed the basic premises, outlined above, for the 1755 prize, and had also sent them to Minister of the Navy Rouillé de Jouy with the support of Duhamel du Monceau (Grognard, "Mémoire sur une nouvelle façon de terminer l'avant des vaisseaux" [1754]). Although he claimed that Rouillé had directed him to build a ship according to those principles, no such ship was ever built. I thank Hubert Berti and Jean Boudriot for this information.

153. Seppings instated a series of improvements in structural framing of British warships from 1806 to 1830, including diagonal frames and filling in of the keel, which considerably reduced the bending of ships and prolonged their useful lives. Some of these improvements had been proposed and built much earlier by the French constructors Gobert and Blaise Ollivier, and by the Dutch constructor William May.

154. Johann Albrecht Euler, "Recherches sur l'arrimage des vaisseaux" (1761); Bossut, "Mémoire sur l'arrimage des vaisseaux" (1761). Bossut reprised his approach in his *Traité élémentaire d'hydrodynamique* (1771), pp. 213–238.

155. Bossut, “Mémoire sur l’arrimage des vaisseaux” (1761/1765); Groignard, “De l’Arrimage des vaisseaux” (1765); Gautier, “De l’Arrimage des vaisseaux” (1765); Bourd  de Villehuet, “De l’Arrimage du navire” (1765). The question was likely proposed to the Academy of Sciences by the East Indies Company, which had been experimenting with water ballast to diminish roll and pitch (Llinares, *Marine, propulsion et technique* [1994], p. 155). In 1789 Burgues de Missiessy-Qu  published *Arrimage des vaisseaux* (Lading of Ships), which proposed a stowage system based on Bourd  de Villehuet’s memoir. All four memoirs were reprinted in the second edition of Bourd  de Villehuet’s *Le Manoeuvrier* (The Maneuverer) in 1814.

156. In 1771 the chevalier de Tr mergat, in a letter to the Royal Academy of the Navy, complained: “This contradiction [of theories] shows how far the solutions of mathematicians are from reality when they do not treat the problem in its generality.” Quoted in Llinares, *Marine, propulsion et technique* (1994), p. 156.

157. Juan y Santacilia, *Examen mar timo* (1771/1992), vol. 2, pp. 305–308.

158. Goldberg, “Intact Stability” (1988), p. 75.

159. Juan y Santacilia, *Examen mar timo* (1771/1992), vol. 2, pp. 407–410. A further analysis of Juan y Santacilia’s work on roll and pitch is given in Sobr n Iruretagoyena and Vuelta Fern ndez, “Breve an lisis de algunos modelos te ricos” (1996).

160. Juan y Santacilia, *Examen mar timo* (1771/1992), vol. 2, p. 98.

161. Carl Sheldon, a member of the Swedish family of constructors, wrote a minor dissertation as a student in 1757 that went completely unnoticed. It examined ships at large angles of heel and principally aimed at calculating the new water plane areas and displacements. Sheldon, *De Subversione Navium* (1757).

162. Atwood, “The Construction and Analysis of Geometrical Propositions” (1796); and Atwood and Vial du Clairbois: “A Disquisition on the Stability of Ships” (1798).

163. Atwood and Vial du Clairbois: “A Disquisition on the Stability of Ships” (1798), p. 249.

Chapter 5: The Great Works

1. Bouguer, *Tra   du navire* (1746), pp. xiv–xv; Deslandes, “Seconde lettre 1.1.1.1 sur la construction des vaisseaux” (1748), pp. 421–425; Demerliac, *La Marine de Louis XIV* (1992), p. 110; Boudriot, *Le Vaisseau trois-ponts du chevalier Tourville* (1998), p. 21. The timing of the model tests is important, as several historians have incorrectly claimed that they were done to prove ideas in Hoste’s book that Tourville opposed, when in fact they happened a decade before the book’s publication.

2. Hoste, *Th orie de la construction des vaisseaux* (1697), pp. ii–iii.

3. *Ibid.*, p. i. Italics in the original.

4. See Timoshenko, *History of Strength of Materials: With a Brief Account of Theory of Elasticity and Theory of Structures* (1953/1983), pp. 15–23, for an account of the works of Galileo and Mariotte.

5. Hoste, “Architecture navale” (1714). Thomas Chaize at the University of Poitiers has analyzed this work; see Chaize, *La Construction navale au 17^{ème} siècle* (1997), and *Étude graphique d’un manuscript de construction navale* (1998).
6. Nicole and Clairaut, “Rapport suivant de l’ouvrage de Mr. Bouguer” (1745), Bouguer, *Traité du navire* (1746), “Privilège du roi” page.
7. Bouguer, letter to Maurepas (January 1734).
8. Thanks to the publishing historian Catherine Bousquet-Bressolier for information from Jombert’s catalogs.
9. Lewis, *Principles of Naval Architecture* (1988).
10. This point is made in the editor’s preface to Bouguer, *Optical Treatise on the Gradation of Light* (1961), p. xi.
11. Anonymous, Review of *Traité du navire* (1747).
12. A complete analysis of *Scientia Navalis* is given in Habicht, “Leonhard Eulers Schiffstheorie” (1978).
13. Simón Calero, *La génesis de la mecánica de los fluidos* (1996), p. 212.
14. Fuss, “Éloge de M. Léonhard Euler” (1783), p. 183.
15. Ibid., p. 184. The original French-language publication of 1773, according to the mathematician Condorcet, had too many grammatical errors to be useful. In 1774 he encouraged Turgot to command another, corrected edition (printed by Jombert in 1776), specifically electing not to inform Euler until after the fact. Euler was later paid 1,000 rubles, worth about \$40,000 today (the previous editions had netted him 2,000 rubles or \$80,000). Translations of Condorcet’s and Turgot’s letters on this subject are at the Euler 2007 Web site, accessed August 2003.
16. For example, a letter from Bouguer to Duhamel du Monceau, dated 22 September 1751, described experiments on the density of seawater that were quoted in *Éléments de l’architecture navale*, p. 362. Bouguer, biographical dossier, Academy of Sciences (undated).
17. Villiers, “De la Lutte contre la maladie du safran” (2001), p. 7.
18. Morineau, *Répertoire de construction* (1752/2005). It was evidently begun in 1751, substantially finished in 1752, but edited up through 1762. My thanks to Gérard Delacroix for his observations.
19. Murray, *Treatise on Ship-building and Navigation* (1754/1765) was principally a series of translated excerpts from *Éléments*, with some from Bouguer’s *Traité du navire*. In Denmark, the chief constructor Henrik Gerner translated (but never published) the work in the 1770s. The manuscript is on display at the Orlogsmuseet (Royal Danish Naval Museum) in Copenhagen.
20. Morales Hernández, “Jorge Juan, en Londres” (1973), pp. 666–667; Soler Pascual, *Viajes de Jorge Juan y Santacilia* (2002), pp. 277–278.

21. An analysis of references to establish the probable dates of authorship for *Examen marítimo* is given in Simón Calero, “La mecánica de los fluidos en Jorge Juan” (2001), pp. 216–219. Some secondary sources insist that Juan y Santacilia wrote a 1752 treatise titled *Teoría del buque y cálculo infinitesimal* (Ship Theory and Infinitesimal Calculus), but no such published book exists and no archive in Spain appears to possess a manuscript with that title.
22. This delay between the completion and the publication of *Examen marítimo* is explored in García-Frías, “Razón histórica del *Examen Marítimo*” (1973).
23. A complete analysis of the fluid mechanics portion of volume 1 is given in Simón Calero, “La mecánica de los fluidos en Jorge Juan” (2001).
24. Juan y Santacilia, *Examen marítimo*, vol. 2 (1771/1992), pp. 339–350.
25. Juan’s symptoms, including muscle stiffness and seizures, as described in Soler Pascual, *Viajes de Jorge Juan y Santacilia* (2002), pp. 355–356, are completely consistent with amebic meningoencephalitis. My thanks to the infectious disease specialist James Campbell for his assistance.
26. Poterat, *Théorie du navire* (1826).
27. A thorough examination of the editions and translations of Chapman’s works is given in Bruzelius, *Maritime History Virtual Archives*, accessed September 2004. Details are also provided throughout D. G. Harris, *F.H. Chapman* (1989), and in the introduction of the 1968 facsimile of *Architectura Navalis Mercatoria*.
28. Thanks to Jan Glete and Jobst Lessenich for their insights on these matters.

Chapter 6: Genius and Engineering

1. Vérin, *La Gloire des ingénieurs* (1993), pp. 19–21.
2. French military engineers are examined in Blanchard, *Les Ingénieurs du roy de Louis XIV à Louis XVI* (1979); Alder, *Engineering the Revolution: Arms and the Enlightenment in France, 1763–1815* (1997); and Langins, *Conserving the Enlightenment* (2004). For the civilian corps, see Picon, *French Architects and Engineers in the Age of Enlightenment* (1998). A back-to-back comparison of the two is given in Gillispie, *Science and Polity in France at the End of the Old Regime* (1980), pp. 479–508.
3. Serbos, “L’École Royale des Ponts et Chaussées” (1964); Taton, “L’École Royale du Génie de Mézières” (1964).
4. Bouguer and Bédior knew one another well, and may have influenced one another’s work; they were correspondents through the Academy of Sciences (Langins, *Conserving the Enlightenment* [2004], p. 225), and their books were contemporaneously published by the house of Claude-Antoine Jombert.
5. Fournier, *Hydrographie* (1643/1667), pp. 1–45.
6. Hahn, “L’Enseignement scientifique des Gardes de la Marine au XVIII^e siècle” (1964); Vergé-Franceschi, *Marine et éducation sous l’ancien régime* (1991), pp. 153–163; Fauque, “Les Écoles d’hydrographie en Bretagne au XVIII^e siècle” (2000).

7. Pritchard, *Louis XV's Navy, 1748–1762* (1987), pp. 38–40, 98–99.
8. Lutun, *La Marine de Colbert, Études d'organisation* (2003), pp. 208–209.
9. Rieth, “Les Débuts de l’enseignement à l’École de Construction de Toulon” (1998), p. 112.
10. Boudriot, *Les Vaisseaux 50 & 64 canons* (1994), p. 9.
11. This process is described in Acerra, “Du Maître de hache à l’ingénieur” (1997).
12. Sturdy, *Science and Social Status* (1995), p. 11.
13. My thanks to Jean Boudriot for explaining to me the importance of this document as a testament to the formation of naval constructors.
14. The relationship between Maurepas and Duhamel du Monceau is carefully analyzed in Villiers, “De la Lutte contre la maladie du safran” (2001).
15. Roger, *Buffon* (1997), pp. 38–46.
16. Biographies of Duhamel du Monceau are Allard, *Henri-Louis Duhamel du Monceau et le ministère de la Marine* (1968); and Dupont de Dinechin, *Duhamel du Monceau* (1999). Papers on his life and work are in Corvol, *Duhamel du Monceau 1700–2000: Un Européen du siècle des lumières* (2001).
17. Thanks go to the naval historian Patrick Villiers for this information.
18. Duhamel du Monceau, “Rapport de Duhamel du monceau sur la petite école de marine qu’il dirige à Paris” (1749). Some secondary sources claim that the first school was established in Toulon, but I have found no indication of this.
19. Duhamel du Monceau, “État des services de M. Duhamel” (1774); Acerra, “Les Constructeurs de la marine” (1985), pp. 297–298; and *Rochefort et la construction navale française* (1993), volume 2, pp. 459–464.
20. Several secondary sources have wrongly indicated that the School of Paris was originally on the ground floor of the Louvre near the Sphinx Court, but this is due to an incorrect interpretation of a description of the school in Jacques-François Blondel’s *Architecture française* (French Architecture), vol. 4 (1756). My thanks to the chief curator of the Louvre historical section, Geneviève Bresc-Bautier, for this information.
21. Aulanier, *Histoire du Palais et du Musée du Louvre*, vol. 3, *Les Trois Salles des états* (1952), pp. 51–53, and vol. 7, *Le Pavillon du roi* (1958), p. 78.
22. For detailed descriptions of Duhamel’s school before 1765, see Poirier, “L’École du Génie Maritime” (1965), pp. 186–188; and Lutun, “Une École pour les constructeurs des vaisseaux du roi de France (1740–1765): Le Projet de Duhamel du Monceau” (1994).
23. Choiseul, *Ordonnance du roi concernant la marine* (1765).
24. I am grateful to Jan Glete for his insights on the language of mathematics and theory in the political organization.

25. Mascart, *La Vie et les travaux du Chevalier Jean-Charles de Borda* (1919), pp. 143–148, 390–392, 481; Rodger, “Navies and the Enlightenment” (2003). My thanks to the naval historian Nicholas Rodger for pointing out the relation between Roquefeuil and Borda, and for providing me with an advance copy of his paper.

26. An excellent overview of this process is given in Pritchard, “From Shipwright to Naval Constructor: The Professionalization of 18th-Century French Naval Shipbuilders” (1987).

27. Anonymous, request to Maurepas concerning the status of royal shipbuilders (undated; c. 1740).

28. Gille, “Les Écoles des constructeurs” (1957); Villiers, *Marine royale, corsaires et trafic* (1991), pp. 535–538; Acerra, *Rochefort et la construction navale française* (1993), volume 2 pp. 464–479; Boudriot, *Les vaisseaux 50 & 64 canons* (1994), p. 21. An example of an approval to the level of ordinary constructor is given in J. Ollivier, letter to Duhamel du Monceau (1765), in which Ollivier, then a senior constructor, attests that Pierre Augustin La Mothe satisfactorily designed a 64-gun ship, calculated stability and resistance, and provided a list of equipment. La Mothe was promoted to ordinary constructor in 1766. Boudriot, *Les vaisseaux 74 à 120 canons* (1995), p. 70.

29. Mascart, *La Vie et les travaux du Chevalier Jean-Charles de Borda* (1919), p. 481.

30. Boudriot, *Les Vaisseaux 50 & 64 canons* (1994), p. 21.

31. Thévenard’s *Mémoires relatifs à la marine* (Memoirs Relative to the Navy), published in 1800, recounted work he had performed in the 1770s. Vial du Clairbois’s work on stability with George Atwood in 1798 (*A Disquisition on the Stability of Ships*) was published in Britain. The first new French work on ship theory after the Revolution, *Développements de géométrie, avec des applications à la stabilité des vaisseaux* (Developments in Geometry: With Applications to the Stability of Vessels), was not published until 1813 by Charles Dupin.

32. Gille, “Les Écoles des constructeurs” (1957), p. 169; Gisserot, “Le Génie maritime et les arsenaux de la marine” (1965), p. 28; Poirier: “L’École du Génie Maritime” (1965), pp. 188–189; Boudriot, *Les vaisseaux 50 & 64 canons* (1994), p. 21; ENSIETA Web site and ENSTA Web site, accessed December 2003.

33. Under the Revolutionary government, Vial du Clairbois dropped the aristocratic “du” and became Citizen Vial-Clairbois.

34. Poirier, “L’École du Génie Maritime” (1965), pp. 188–189.

35. Capel Sáez, Sánchez, and Moncada, *De Palas á Minerva* (1988), pp. 19–25.

36. An excellent overview of the professionalization of the Spanish navy is given in Arroyo, “Las enseñanzas de nautical en el siglo XVIII” (1994). A close look at the Navy Guards is provided in Lafuente and Sellés, *El observatorio de Cadíz (1753–1831)* (1988); López Sánchez, Valera Candel, & López Fernández, “La Academia de Guardias Marinas de Cartagena (1776–1824)” (1995); and Blanco Núñez, *La Armada española en la primera mitad del siglo XVIII* (2001), pp. 63–86.

37. López Sánchez, Valera Candel, López Fernández, “La Academia de Guardias Marinas de Cartagena (1776–1824)” (1995), p. 3; Pando Villarroya, *Jorge Juan y Santacilia, marino* (1984), p. 111.

38. See La Parra López, *El regente Gabriel Ciscar* (1995), for a complete biography.

39. Jorge Juan arrived in London in March 1749, and through the intervention of Ulloa, who had been made a Fellow of the Royal Society after his capture by the British navy while returning from Peru in 1745, was elected a Fellow in November 1749 for his work on geodesy. Royal Society Web site, accessed December 2003.

40. This astonishing feat of industrial espionage is described in Morales Hernández, “Jorge Juan, en Londres” (1973); Lafuente and Peset, “Política científica y espionaje industrial en los viajes de Jorge Juan y Antonio de Ulloa” (1981); and Merino Navarro, *La armada española en el siglo XVIII* (1981), pp. 68–71, 100–103.

41. Artiñano y de Galdácano, *La arquitectura naval española* (1920), p. 228; Harbron, *Trafalgar and the Spanish Navy* (1988), pp. 35–39; Juan-García Aguado, *José Romero Fernández de Landa* (1998), pp. 19–20.

42. Gautier, “De l’Arrimage des vaisseaux” (1765).

43. Merino Navarro, *La armada española en el siglo XVIII* (1981), pp. 49–53; Acerra and Merino Navarro, “Jean-François Gautier, Vie et influence d’un ingénieur marginal” (1985), pp. 8–9; Harbron, *Trafalgar and the Spanish Navy* (1988), pp. 40–41; Juan-García Aguado, *José Romero Fernández de Landa* (1998), pp. 20–21.

44. The Spanish Corps of Naval Engineers is discussed in UPM ETSIN, *II centenario de las enseñanzas de ingeniería naval* (1975), pp. 5, 27–29; Merino Navarro, “Les Techniciens de haut niveau dans les arsenaux espagnols” (1981), pp. 1087–1090; Acerra and Merino Navarro, “Jean-François Gautier: Vie et influence d’un ingénieur marginal” (1985), p. 10; Juan-García Aguado, *José Romero Fernández de Landa* (1998), pp. 30–31; Sánchez Carrión and Cerrolaza Asenjo, “Solución al enigma de los orígenes del Cuerpo de Ingenieros de Marina” (2004). Thanks go to José Maria Sánchez Carrión for additional information.

45. Merino Navarro, “Les Techniciens de haut niveau dans les arsenaux espagnols” (1981), p. 1091; Juan-García Aguado, “Las características operativas de los navíos y fragatas del siglo XVIII” (1996), and *José Romero Fernández de Landa* (1998), pp. 81–89, 125, 305–307.

46. Merino Navarro, “Les Techniciens de haut niveau dans les arsenaux espagnols” (1981), p. 1091; Harbron: *Trafalgar and the Spanish Navy* (1988), p. 46; Juan-García Aguado, *José Romero Fernández de Landa* (1998), pp. 22–23.

47. D. G. Harris, “Francis Sheldon in Denmark 1686–1690” (1997); Bellamy, “English Master Shipwrights to the Danish Crown 1570–1690” (1998).

48. The history of the Naval Cadets Academy is given in Seerup, *Søkadetakademiet i oplysningstiden* (2001).

49. See Rasmussen, “The Royal Danish-Norwegian Dockyard: Innovation, Espionage and Centre of Technology” (1993), pp. 46–49; and Bjerg and Erichsen, *Danske orlogsskibe 1690–1860* (1980), pp. 199–200.

50. Bjerg and Erichsen, *Danske orlogsskibe* (1980), pp. 36–38.

51. Holmberg, “Svenska flottans fartygstyper och fartygsbyggen” (1963), pp. 180, 188; D. G. Harris, *F. H. Chapman* (1989), pp. 159–163. Naval historians Jan Glete and Lars Bruzelius graciously provided additional information.

52. Macleod, “The Shipwrights of the Royal Dockyards” (1925); and, “Shipwright Officers of the Royal Dockyards” (1925); Coles, “The Contribution of British Defence Departments to Technical Education and Instruction from About 1700” (1984), pp. 198–204.

53. My thanks to Richard Channon, clerk at the Worshipful Company of Shipwrights, for providing me information and literature on this subject.

54. Glete, *Navies and Nations* (1993), volume 1 pp. 287–288. By the turn of the nineteenth century, financial difficulties forced both the Spanish and French navies to turn to commercial shipyards and suppliers to supplement government dockyards.

55. Brown, *A Century of Naval Construction* (1983), pp. 25–26; Haas, “The Best Investment Ever Made” (1990), pp. 325–327, and *A Management Odyssey: The Royal Dockyards, 1714–1914* (1994), pp. 45–52.

56. D. K. Brown, *A Century of Naval Construction* (1983), pp. 52–62.

57. Dirkzwager, “De voor geschiedenis van de opleiding tot scheepsbouwkundig ingenieur aan de Technische Universiteit Delft” (1994); Lemmers, *Techniek op schaal* (1996), pp. 152–153.

58. Fausto had translated Aristotle’s *Mechanics* into Italian, a project which possibly inspired some of his thinking. However, as explained in chapters 3 and 4, Aristotle’s “virtual velocity” model of the lever was qualitative only and could not provide practical results. Accounts of Fausto’s trials are given in Lane, *Venetian Ships and Shipbuilders of the Renaissance* (1934/1979), pp. 64–71; Concina, “Humanism on the Sea” (1988), and *Navis: L’umanesimo su mare* (1990), pp. 71–99.

59. Renn and Valleriani, “Galileo and the Challenge of the Arsenale” (2001).

60. The history of the School of Naval Architecture is found in Zanelli, “La Scuola di ‘Naval Architettura’ nell’Arsenale di Venezia” (1997).

61. Marzari, “L’arte della progettazione e della costruzione navale a Trieste tra il XVIII e il XIX secolo” (1998), p. 183.

62. Hahn, *The Anatomy of a Scientific Institution* (1971), pp. 237–239.

63. Dhombres and Dhombres, *Naissance d’un pouvoir: Sciences et savants en France, 1793–1824* (1989), pp. 346–347. Another recent view of scientific activity in Revolutionary France is given in Gillispie, *Science and Polity in France: The Revolutionary and Napoleonic Years* (2004).

64. McClellan, *Science Reorganized* (1985), pp. 253–257.
65. Sewell, “On the Importance of the Study of Shipbuilding” (1791).
66. Johns, “An Account of the Society for the Improvement of Naval Architecture” (1910); D. K. Brown, “How It All Began” (1991).
67. Hall, *The Scientific Revolution 1500–1800* (1954/1962), pp. xii–xiii.
68. The relationship of theory, iterative design, and naval architecture in ship construction is explored in McGee, “From Craftsmanship to Draftsmanship” (1999).
69. This process was quite similar to the development of criteria for longitudinal stability of aircraft from 1918 to 1936, described in Vincenti, *What Engineers Know and How They Know It* (1990), pp. 63–66.
70. John Scott Russell would develop the wave-line theory of resistance, which was in vogue during the mid-1800s, and was one of the first to adopt and explain the system of longitudinal construction for iron ships as a means of improving their strength. William Fairbairn, a bridge builder, would develop the “balance-on-a-wave” theory to define the strength requirements for the hull girder. William Froude, who began his career in hydraulics, would become famous for developing a rational theory and measurement of rolling, and for creating the system and theory of experimental hydrodynamics that, for the first time, gave a reasonably accurate estimation of resistance and power. The influence of Brunel and others in the development of modern naval architecture will form the centerpiece of my next work, *Bridging the Seas: The Development of Naval Architecture in the Industrial Age, 1800–2000*.
71. An examination of this legacy, and an overview of several modern corps of constructors, is found in Ferreiro, “Genius and Engineering: The Naval Constructors of France, Great Britain and the United States” (1998/1999).

Epilogue: Promised Land

1. Anthiaume, “Pierre Bouguer (1698–1758)” (1914), p. 140. “Rue des Postes” is the address on his later correspondence with Leonhard Euler (Bouguer, “Lettres de Bouguer à Euler” [1966]). In one of those letters (23 November 1752, p. 234) Bouguer asked Euler to send a package to him via a friend, in order to avoid customs duties; he then apologized for not recopying the scribbling in his letter—he could not afford more paper. I thank René Ghislaine for identifying rue Lhomond as the former rue des Postes (that name can still be seen in the stonework of the buildings).
2. Pierre Bouguer, “Relation abrégée du voyage fait au Pérou” (1744).
3. Erickson, “The French Academy of Sciences Expedition to Spanish America, 1735–1744” (1955), pp. 313–319.
4. A review of the quarrel as discussed in the journals of the day is given in Marcil, “La Presse et le compte rendu de récits de voyage scientifique: Le cas de la querrelle entre Bouguer et La Condamine” (1999).

5. I thank the science historian Jean Dhombres for this observation.
6. Condorcet, “Éloge de M. de La Condamine” (1774), p. 108.
7. See Maheu, “Bibliographie de Pierre Bouguer (1698–1758)” (1966), and “La Vie scientifique au milieu du XVIII^e siècle: Introduction à la publication des lettres de Bouguer à Euler” (1966).
8. Bouguer, “Lettres de Bouguer à Euler” (1966).
9. Chesnais, “Les Trois Bouguer et Le Croisic “ (2002), p. 26. Grandjean de Fouchy, in Bouguer’s eulogy, mistakenly gave the year of Jean Bouguer’s death as 1757.
10. Bouguer, “Lettres de Bouguer à Euler” (1966), p. 241.
11. Grandjean de Fouchy, “Éloge de M. Bouguer” (1758), pp. 134–135.
12. Ibid., p. 135; Bouguer, *Optical Treatise on the Gradation of Light* (1961), p. 5; La Condamine, “Lettre de Monsieur de La Condamine à M. *** sur le sort des astronomes” (1773). My thanks to the infectious disease specialist James Campbell for his useful insights into amebic diseases.
13. Laberthionie, *Relation de la conversion et la mort de M. Bouguer* (1784). Laberthionie wrote this book to argue against the “irreligion” of the scientists of his day (Sturdy, *Science and Social Status: The Members of the Académie des Sciences, 1666–1750* [1995], p. 397). However, the historian Roland Lamontagne argues that Bouguer never really left the Church and that the conversion was less dramatic than Laberthionie portrayed. Lamontagne, *La Vie et l’oeuvre de Pierre Bouguer* (1964), pp. 91–94.
14. I thank the Mayor’s Office, City of Paris.
15. Le Monnier, letter to Minister of the Navy Choiseul on the inclining of *Royal Louis* (4 April 1763).

Bibliography

Abbreviations

AE. Acta Eruditorum (Transactions of the Learned). Leipzig, 1682–1731.

ANF. Archives Nationales de France (National Archives of France). Paris.

BATM[A]. Bulletin de l'Association Technique Maritime [et Aéronautique] (Bulletin of the Maritime [and Aeronautic] Technical Association). Paris, 1890–present.

BNF. Bibliothèque Nationale de France (National Library of France). Paris.

CP. Commentarii Academiae Scientiarum Imperialis Petropolitanae (Commentaries of the Imperial Academy of Sciences of Saint Petersburg). Saint Petersburg, 1726–1746.

HASB. Histoire l'Académie Royale des Sciences et des Belles-lettres de Berlin (History of the Royal Academy of Sciences and Literature of Berlin). Berlin, 1745–1769.

HMAS. Histoire et mémoires de l'Académie Royale des Sciences de Paris (History and Memoirs of the Royal Academy of Sciences of Paris). Paris, 1699–1790.

JS. Journal des sçavans (Journal of Scholars). Paris, 1665–1792.

JT. Journal de Trévoux, also known as *Mémoires pour l'histoire des sciences et des Beaux-arts* (Memoirs for the History of Science and Arts). Trévoux, 1701–1767.

KVAH. Kongliga [now Kungliga] Vetenskapsakademien nya handlingar (New Proceedings of Royal Swedish Academy of Sciences). Stockholm, 1739–present.

MAS. Mémoires de l'Académie des Sciences de l'Institut de France (Memoirs of the Academy of Sciences of the Institute of France). Paris, 1849–1949.

MNM. Museo Naval de Madrid (Naval Museum of Madrid). Madrid.

NAP. Nova Acta Academiae Scientiarum Imperialis Petropolitanae (New Transactions of the Imperial Academy of Sciences in St. Petersburg). Saint Petersburg, 1783–1802.

NCP. Novi Commentarii Academiae Scientiarum Imperialis Petropolitanae (New Commentaries of the Imperial Academy of Sciences of Saint Petersburg). Saint Petersburg, 1747–1775.

NMM. National Maritime Museum. Greenwich, England.

PEM. Peabody-Essex Museum, Phillips Library. Salem, MA.

PTRS. *Philosophical Transactions of the Royal Society*. London, 1665–present.

PVAS. *Procès-verbaux de l'Académie Royale des Sciences* (Oral Proceedings of the Academy of Sciences). Paris, 1681–1792.

RPRP. *Recueils des pièces qui ont remporté les prix de l'Académie Royale des Sciences* (Collection of Works That Have Taken the Prizes of the Royal Academy of Sciences). Paris, 1720–1792.

SHDMV. Archives of Service Historique de la Défense, Département Marine, Vincennes. Vincennes.

TIESIS. *Transactions of the Institution of Engineers and Shipbuilders in Scotland*. Glasgow, 1857–present.

TNECIES. *Transactions of the North-East Coast Institution of Engineers and Shipbuilders*. Newcastle-upon-Tyne, England, 1885–1992.

T[R]INA. *Transactions of the [Royal] Institution of Naval Architects*. London, 1860–present.

TSNAME. *Transactions of the Society of Naval Architects and Marine Engineers*. New York/Jersey City, NJ, 1893–present.

Primary Sources

Académie Royale de Marine. *Mémoires de l'Académie Royale de Marine* (Memoirs of the Royal Academy of Navy). Brest: Malassis, 1773.

Anonymous. Review of the book by Renau d'Elizagaray, *Mémoire où est démontré un principe de la mécanique des liqueurs dont on s'est servi dans la "Théorie de la manoeuvre des vaisseaux" et qui a été contesté par M. Huygens* (Memoir Wherein Is Demonstrated a Principle of the Mechanics of Liquids Which Served in the "Theory of Maneuvering of Vessels" and Which Was Contested by Mr. Huygens). *JS* (December 1713), pp. 549–554.

Anonymous. Request to Maurepas concerning the status of royal shipbuilders. Cornell University, Maurepas Collection, box 8, folder 14 (undated; ca. 1740).

Anonymous. "Rôle de désarmement du *Triton*" (End-of-voyage Roster of *Triton*). Archives Départementales de Loire-Atlantique (Departmental Archives of Loire-Atlantique), côte provisoire 120 J 378/B (1744).

Anonymous. Review of *Traité du navire, de sa construction et de ses mouvemens* (Treatise of the Ship, of Its Construction and Its Movements). *JS* (January 1747), pp. 47–53.

Anonymous. "Consulta a varias personas en el año de 1781 sobre las reformas que hacen con la Construcción Naval para aumentar la Velocidad de la marcha, y contestación de una de aquellas" (Consultations with Various People in the Year 1781 on the Reforms Made to Naval Con-

struction in Order to Increase the Velocity of Movement, and the Response of One of Them). MNM, manuscript 2215.6 (Cartagena, 31 March 1782).

Anonymous. *The Shipbuilder's Repository; or a Treatise on Marine Architecture* London: Parsley, ca. 1782. Facsimile, Rotherfield, UK: Jean Boudriot Publications, 1992.

Anonymous. "Remarks on the Forms and Properties of Ships, by an Officer of Rank and Experience in the Navy." In *A Collection of Papers on Naval Architecture: Originally Communicated Through the Wrapper of the European Magazine*, edited by John Sewell, pp. 10–12. London: Sewell, 1800.

Aristotle. *The Complete Works of Aristotle*, edited by Jonathan Barnes. Princeton, N.J.: Princeton University Press, 1984.

Atwood, George. "The Construction and Analysis of Geometrical Propositions, Determining the Positions Assumed by Homogeneous Bodies Which Float Freely, and at Rest, on a Fluid's Surface; also Determining the Stability of Ships and of Other Floating Bodies." *PTRS* (1796), pp. 46–130.

Atwood, George, and Honoré-Sébastien Vial du Clairbois. "A Disquisition on the Stability of Ships." *PTRS* (1798), pp. 201–310.

Barthès de Marmorières, Guillaume. *Mémoires d'agriculture et de mécanique, dans lesquels on propose des pratiques simples et nouvelles, relatives au bien de l'état et des avantages particuliers de la province du Languedoc: Avec le Moyen de remédier aux abus du jaugeage des vaisseaux dans tous les ports du royaume* (Memoirs on Agriculture and Mechanics, in Which Are Proposed New and Practical Methods Relative to the Good of the State and Particularly Languedoc: With the Means to Remedy the Abuses of Admeasurement of Vessels in All the Ports of the Kingdom). Paris: Prault, 1762.

Bélibidor, Bernard Forêt de. *Architecture hydraulique; ou l'Art de conduire et de ménager les eaux pour les différents besoins de la vie* (Hydraulic Architecture; or the Art of Conducting and Managing the Waters for the Different Needs of Life), 4 vols. Paris: Charles-Antoine Jombert, 1737–1753.

Bernoulli, Daniel. "Examen Principiorum Mechanicae, et Demonstrationes Geometricae de Compositione et Resolutione Virium" (Examination of the Principles of Mechanics and Geometric Demonstrations of the Composition and Resolution of Forces. *CP*, 1 (1726). Translated by Jean Dhombres as "Examen des principes de la mécanique et démonstrations géométriques de la composition et de la résolution des forces." *Sciences et techniques en perspective* (Science and Technology in Perspective) vol. 11 (1987), pp. 39–58.

Bernoulli, Daniel. "Theoria Nova de Motu Aquarum per Canales Quosunque Fluentium" (New Theory on the Movement of Water Flowing Through Any Canal). *CP* (1727), pp. 111–125.

Bernoulli, Daniel. "Commentationes de Statu Aequilibræ Corporum Humido Insidentium" (Commentaries on the State of Equilibrium of Floating Bodies). *CP* (1738), pp. 147–163 and table XIII. French translation by Frans Cerulus at <http://zeus.fltr.ucl.ac.be/ciehs/Sources.htm>, accessed September 2002. Annotated in Cerulus, "Comments on Daniel Bernoulli and Floating

Bodies." In *Die Werke von Daniel Bernoulli* (The Works of Daniel Bernoulli) vol. 6. Basel: Birkhäuser Verlag.

Bernoulli, Daniel. *Hydrodynamica, sive de Viribus et Motibus Fluidorum Comentarii* (Hydrodynamics, or Commentaries on Forces and Motions of Fluids). Strasbourg: Dulsecker, 1738. Translation by Thomas Carmody and Helmut Kobus in *Hydrodynamics by Daniel Bernoulli and Hydraulics by Johann Bernoulli*. New York: Dover, 1968.

Bernoulli, Daniel. "De Motibus Oscillatoriis Corporum Humido Insidentium" (On the Oscillating Movements of Floating Bodies). *CP* (1739), pp. 100–115 and table I. French translation by Frans Cerulus at <http://zeus.fltr.ucl.ac.be/ciehs/Sources.htm>, accessed 16 September 2002. Annotated in Cerulus, "Comments on Daniel Bernoulli and Floating Bodies." In *Die Werke von Daniel Bernoulli* (The Works of Daniel Bernoulli); vol. 6. Basel: Birkhäuser Verlag.

Bernoulli, Daniel. "Principes hydrostatiques et mécaniques, sur la question 'Quelle est la meilleure manière de diminuer le roulis et le tangage d'un navire'" (Hydrostatic and Mechanical Principles on the Question "What Is the Best Method to Reduce the Roll and Pitch of a Ship") 1757 Prize, *RPRP*, vol. 8 (1771). Reprinted as *Principes hydrostatiques et mécaniques*. Paris: Geurin et Delatour, 1771. Annotated in Cerulus, "Comments on *Principes hydrostatiques et mécaniques*." In *Die Werke von Daniel Bernoulli* (The Works of Daniel Bernoulli), vol. 8. Basel: Birkhäuser Verlag, 2004.

Bernoulli, Jacob. "Curvatura veli" (On the Curve of Sails), *AE* (1692), pp. 202–207. Reprinted in Jacobus Bernoulli Basileensis, *Opera*, pp. 481–490. Geneva: Cramer, 1744.

Bernoulli, Jacob. "Explicationes, Annotationes et Additiones ad Ea, Quae in Actis Sup. Anni de Curva Elastica, Isochrona Paracentrica, et Velaria, Hinc inde Memorata, et Partim Controversa Leguntur; Ubi de Linea Mediarum Directionum, Aliisque Novis" (Explanations, Annotations and Additions to the Acts of the Previous Year on Elastic Curves, Isochronous Paracentric [curves] & Sails, from that Memoir, and Gathered from that Debate; Where the Line Measures a New and Different Direction). *AE* (December 1695), pp. 357–553. Reprinted in Jacob Bernoulli, *Opera*, pp. 639–663. Geneva: Cramer, 1744.

Bernoulli, Jacob. "Problema Beaunianum Universalis Conceptum, sive Solutio Aequationis Nupero Decembri Propositae a $dy = yp \, dx + by \, n \, q \, dx$, cum Aliis Quibusdam Annotatis" (Concept of a Universal Problem from Beaune, or Solution to the Equations Appearing in the Proposition in the December Edition. . . Which Is Another Thing Noted). *AE* (July 1696), pp. 332–337. Reprinted in Jacob Bernoulli, *Opera*, pp. 731–739. Geneva: Cramer, 1744. Also reprinted in *Die Streitschriften von Jacob und Johann Bernoulli* (Polemics of Jacob and Johann Bernoulli), edited by Herman Goldstine and Patricia Radelet-de Grave, pp. 213–221. Basel: Birkhäuser, 1991.

Bernoulli, Jacob. "De Celeritate et Declinatione (Dérive) Navis" (On the Speed and Dérive of Ships). In Jacob Bernoulli, *Opera*, pp. 1057–1062. Geneva: Cramer, 1744.

Bernoulli, Jacob. "Celeritates Navis a Quietate Inchoatas Usque ad Maximam Invenire" (The Speed of Ships from Rest Until Finding the Maximum Point). In Jacob Bernoulli, *Opera*, pp. 1080–1082. Geneva: Cramer, 1744.

Bernoulli, Jacob. *Jacobi Bernoulli Basileensis: Opera*. Geneva: Cramer, 1744.

Bernoulli, Johann. "Excerpta Litteris" (Excerpt from the Letter [to Leibniz, on the solid of least resistance]) *AE* (1699), 514–516. Reprinted in Johann Bernoulli, *Opera Omnia*, vol. 1, pp. 307–311. Lausanne and Geneva: Bousquet, 1742. Also edited by J. E. Hofman. Hildesheim: Olms, 1968.

Bernoulli, Johann. "De Solido Rotundo Minimae Resistentiae" (On the Round Solid of Least Resistance). *AE* (1700), pp. 208–214. Reprinted in Johann Bernoulli, *Opera Omnia*, vol. 1, pp. 315–320. Lausanne and Geneva: Bousquet, 1742. Also edited by J. E. Hofman. Hildesheim: Olms, 1968.

Bernoulli, Johann. *Essay d'une nouvelle théorie de la manoeuvre des vaisseaux* (Essay on a New Theory of the Maneuvering of Vessels). Basel: König, 1714.

Bernoulli, Johann. "Hydraulica, Nunc Primum Detecta ac Demonstrata Directe ex Fundamentis Pure Mechanicis" (Hydraulics, Now First Discovered And Proved from Purely Mechanical Foundations). In Johann Bernoulli, *Opera Omnia*, vol. 4, pp. 387–493. (Lausanne and Geneva: Bousquet, 1742). Translated by Thomas Carmody and Helmut Kobus in *Hydrodynamics by Daniel Bernoulli and Hydraulics by Johann Bernoulli*. New York: Dover, 1968.

Bernoulli, Johann. *Johannis Bernoulli Opera Omnia* (Johann Bernoulli's Complete Works). Lausanne and Geneva: Cramer, 1742. Also edited by J. E. Hofman. Hildesheim: Olms, 1968.

Bernoulli, Johann. *Der Briefwechsel von Johann Bernoulli* (The Correspondence of Johann Bernoulli), edited by Otto Spiess. Basel: Birkhäuser Verlag, 1955.

Bignon, Jean-Paul. Letter to Pierre Bouguer nominating him to the geodesic mission. BNF, manuscript 22235, folio 289 (18 December 1734).

Bignon, Jean-Paul. Letter to Minister of the Navy Maurepas, relaying Bouguer's acceptance to serve on the geodesic mission. BNF, manuscript 22235, folio 291 (26 December 1734).

Bignon, Jean-Paul. Letter to Minister of the Navy Maurepas, confirming Bouguer's acceptance to the geodesic mission. BNF, manuscript 22235, folio 292 (29 December 1734).

Blondel, Jacques-François. *Architecture française, ou Recueil des plans, élévations, coupes et profils des églises, maisons royales, palais, hôtels, etc.* (French Architecture, or Collection of Plans, Elevations, Sections and Profiles of Churches, Royal Houses, Palaces, Halls, etc.). 4 vols. Paris: Charles-Antoine Jombert, 1752–1756.

Bonjean, Antoine Nicolas François. *Nouvelles échelles de déplacement: Et de Centre de gravité de carène, pour des vaisseaux de guerre* (New Scales of Displacement; And of the Center of Gravity of the Bottom, for Vessels of War). Lorient: Baudoin, 1810.

Bonjean, Antoine Nicolas François. "Etat de service" (State of Service). SHDMV, CC7 Alpha 254 (January 1822).

Borda, Jean-Charles de. "Expériences sur la résistance des fluides" (Experiments on the Resistance of Fluids). *HMAS* (1763), pp. 358–376.

Borda, Jean-Charles de. "Expériences sur la résistance des fluides" (Experiments on the Resistance of Fluids). *HMAS* (1767), pp. 495–503.

Bossut, Charles. "Mémoire sur l'arrimage des navires" (Memoir on the Lading of Ships), 1761 prize submission. *RPRP*, 7 (1769). Resubmitted as "Traité de l'arrimage des vaisseaux" (Treatise on the Lading of Vessels), 1765 prize submission. *RPRP*, 9 (1777). Reprinted in Bossut, Charles: *Traité de l'arrimage des vaisseaux*. Paris: Bachelier, 1810.

Bossut, Charles. *Traité élémentaire d'hydrodynamique* (Elementary Treatise on Hydrodynamics). Paris: Claude-Antoine Jombert, 1771.

Bossut, Charles, Jean Le Rond D'Alembert, and Marie Jean Antoine Nicolas de Caritat, marquis of Condorcet. *Nouvelles Expériences sur la résistance des fluides* (New Experiments on the Resistance of Fluids). Paris: Charles-Antoine Jombert, 1777.

Bossut, Charles de. "Nouvelles Expériences sur la résistance des fluides" (New Experiments on the Resistance of Fluids). *HMAS* (1778), pp. 353–380.

Bouguer, Jean. *Traité complet de la navigation, contenant les propositions et pratiques de géométrie, de la sphère et d'astronomie, etc.* (Complete Treatise of Navigation, Containing the Propositions and Practice of Geometry, of the Sphere and of Astronomy, etc.) Paris: Guignard, 1698; Paris: Henqueville, 1706.

Bouguer, Pierre. "Sur le Jaugeage des vaisseaux" (On the Admeasurement of Vessels). *PVAS* (11 February 1722), pp. 39–46.

Bouguer, Pierre. Letter to Minister of the Navy Maurepas proposing that hydrographers, examine all ships logs to improve information on navigation; ANF, Fonds Marine, C7 40, dossier Bouguer, folios 2–5 (Le Croisic, 1 January 1726).

Bouguer, Pierre. Letter to Minister of the Navy Maurepas asking to visit Paris to submit additional points for his treatise on masting. ANF, Fonds Marine, C7 40, dossier Bouguer, folios 6–7 (Le Croisic, 17 February 1727).

Bouguer, Pierre. "De la Mâturation des vaisseaux" (On the Masting of Vessels), 1727 prize. *RPRP*, 1 (1752). Reprinted in Bouguer, *De la Mâturation des vaisseaux*. Paris: Claude Jombert, 1728.

Bouguer, Pierre. Letter to Minister of the Navy Maurepas requesting additional financial support. ANF, Fonds Marine, C7 40, dossier Bouguer, folios 10–11 (1729).

Bouguer, Pierre. Letter to Minister of the Navy Maurepas requesting funds for research. ANF, Fonds Marine, C7 40, dossier Bouguer, folios 12–13v (Le Croisic, 16 October 1730).

Bouguer, Pierre. "Sur de Nouvelles Courbes auxquelles on peut donner le nom de lignes de poursuite" (On the New Curves Which One Can Give the Name Lines of Pursuit). *HMAS* (1732), pp. 1–14.

Bouguer, Pierre. "Une Base qui est exposée au choc d'un fluide étant donnée, trouver l'espèce de conoïde dont il faut la couvrir, pour que l'impulsion soit la moindre qu'il est possible" (Given a Base Exposed to the Shock of a Fluid, Find the Type of Conoid Which Must Cover It, So That the Impulsion is the Least Possible). *HMAS* (1733), pp. 85–107.

Bouguer, Pierre. Letter to Jean-Paul Bignon requesting additional support for his experiments. BNF, manuscript 22226, folios 177–180 (Havre de Grace, 13 January 1733).

Bouguer, Pierre. “Comparaison des deux loix que la terre et les autres planètes doivent observer dans la figure que la pesanteur leur fait prendre” (Comparison of Two Laws That the Earth and Other Planets Must Observe in the Shape Caused by Their Weight). *HMAS* (1734), pp. 21–40.

Bouguer, Pierre. Letter to Minister of the Navy Maurepas on his plans for a treatise on the ship. ANF, Fonds Marine, C7 40, dossier Bouguer, folios 15–17 (Le Havre, 13 January 1734).

Bouguer, Pierre. Letter to Minister of the Navy Maurepas on his astronomical observations. ANF, Fonds Marine, C7 40, dossier Bouguer, folios 18–19 (Le Havre, 21 November 1734).

Bouguer, Pierre. Certification of Pierre Fouré, master of *Triton*, that Fouré is “very capable of exercising pilotage on any long-distance voyages.” Smithsonian Institution, Dibner collection, MSS 155A RB NMAH (Nantes, 3 June 1744).

Bouguer, Pierre. “Relation abrégée du voyage fait au Pérou par Messieurs de l’Académie Royale des Sciences, pour mesurer les degrés du méridien aux environs de l’équateur, et en conclure la figure de la terre” (Abridged Relation of the Voyage to Peru by Gentlemen of the Academy of Sciences, to Measure the Degrees of the Meridian near the Equator, and to Conclude the Figure of the Earth). *HMAS* (1744), pp. 249–297.

Bouguer, Pierre. “Éclaircissemens sur le problème de la mâtûre des vaisseaux” (Clarifications on the Problem of the Masting of Vessels). *HMAS* (1745), pp. 309–329.

Bouguer, Pierre. “De l’Impulsion des fluides sur les pîoues faites en pyramidoïdes, dont la base est un trapèze” (On the Impulsion of Fluids on Bows in the shape of Pyramids with a Trapezoidal Base). *HMAS* (1746), pp. 237–283.

Bouguer, Pierre. *Traité du navire, de sa construction, et de ses mouvemens* (Treatise of the Ship, Its Construction and Its Movements). Paris: Charles-Antoine Jombert, 1746.

Bouguer, Pierre. Letter on the speed of ships. *JT* (1748), pp. 1028–1046.

Bouguer, Pierre. “Mémoire sur la forme des corps les plus propres à tourner sur eux-mêmes, lorsqu’ils sont poussés par une de leurs extrémités, ou par tout autre point” (Memoir on the Form of the Most Appropriate Bodies to Turn About Themselves, When They Are Pushed by one of Their Extremities, or by Any Other Point). *HMAS* (1751), pp. 1–22.

Bouguer, Pierre. *Nouveau Traité de navigation, contenant la théorie et la pratique du pilotage* (New Treatise of Navigation, Containing the Theory and Practice of Piloting). Paris: Guérin et Delatour, 1753.

Bouguer, Pierre. “Solutions des principaux problèmes de la manoeuvre des vaisseaux” (Solutions to the Principal Problems of the Maneuvering of Vessels). *HMAS* (1754), pp. 342–368.

Bouguer, Pierre. “Mémoire sur le mouvement d’oscillation des corps qui flottent sur les liqueurs” (Memoir on the Oscillatory Movement of Bodies That Float on Liquids). *HMAS* (1755), pp. 481–495.

Bouguer, Pierre. "Seconde Mémoire sur les principaux problèmes de la manoeuvre des vaisseaux" (Second Memoir on the Principal Problems of the Maneuvering of Vessels). *HMAS* (1755), pp. 355–369.

Bouguer, Pierre. *De la Manoeuvre des vaisseaux, ou Traité de mécanique et de dynamique: Dans lequel on réduit a des solutions très simples les problèmes de marine les plus difficiles, qui ont pour objet le mouvement du navire* (On the Maneuvering of Vessels, or Treatise on Mechanics and Dynamics: In Which Very Simple Solutions Are Given to the Most Difficult Naval Problems, Which Are Aimed at the Movement of the Ship). Paris: Guérin et Delatour, 1757.

Bouguer, Pierre. *Traité d'optique sur la gradation de la lumière* (Optical Treatise on the Gradation of Light), edited by Nicolas-Louis de La Caille. Paris: Guérin et Delatour, 1760. Translated by W. E. Knowles Middleton as *Optical Treatise on the Gradation of Light*. Toronto: University of Toronto Press, 1961.

Bouguer, Pierre. "Lettres de Bouguer à Euler" (Letters from Bouguer to Euler). edited by Roland Lamontagne. *Revue d'histoire des sciences* (Review of the History of Sciences), (1966), vol. 19, pp. 226–246.

Bouguer, Pierre. Biographical dossier. Library of the French Academy of Sciences (undated), 433 pages, noncategorized. Described in Roland Lamontagne, "Pierre Bouguer: Dossiers personnels conservés aux Archives de France et à l'Académie des Sciences de Paris" (Pierre Bouguer: Personal Dossiers Conserved at the French Archives and at the Academy of Sciences of Paris). Unpublished manuscript in University of Montreal Archives, Fonds Roland Lamontagne (P 130) (1997).

Bourdé de Villehuet, Jacques-Pierre. "De l'Arrimage du navire" (On the Lading of Ships), 1765 prize. *RPRP*, 9. (1777); reprinted in Bossut, *Traité de l'arrimage des vaisseaux*, 1810.

Bourdé de Villehuet, Jacques-Pierre. *Le Manoeuvrier, ou Essai sur la théorie et la pratique des mouvements du navire et des évolutions navales* (The Maneuverer, or Essay on the Theory and Practice of Ship Motions and Naval Evolutions). Paris: Guérin & Delatour, 1765; 1769. Translated by Chevalier de Sauseuil as *The Manueverer, or skilful seaman*. London: S. Hooper, 1788. Other editions, Paris: Bachelier, 1814; 1832. Facsimile, Levandou: Éditions du Layet, 1987.

Bourne, William. *A Booke Called the Treasure for Traveilers, Divided into Five Books, Contaynyng Very Necessary Matters for All Sortes of Traveilers Eyther by Sea or by Land*. London: Thomas Woodcocke, 1578. Facsimile, Norwood, NJ: W. J. Johnson, 1979.

Burgues de Missiessy-Quîès, Edouard Thomas, count of. *Arrimage des vaisseaux* (Lading of vessels). Paris: Imprimerie Royale, 1789.

Bushnell, Edmund. *The Complete Shipwright*. London: George Hurlock, 1664.

Camus, Charles Étienne Louis. "De la Mâturation des vaisseaux" (On the Masting of Vessels), 1727 prize. *RPRP*, 2 (1752). Reprinted in Bouguer, *De la Mâturation des vaisseaux*. Paris: Claude Jombert, 1728.

Cayley, George. "On Aerial Navigation." *Nicholson's Journal of Natural Philosophy, Chemistry and the Arts*, pt. 3 (March 1810).

Chapman, Fredrik Henrik af. *Architectura Navalis Mercatoria* (Merchant Naval Architecture). Stockholm: Hans George Lange, 1768. English translation and facsimile, edited by Ernest Henriot. New York: Praeger, 1968.

Chapman, Fredrik Henrik af. *Tractat om skepps-byggeriet, tillika med förklaring och bevis öfver Architectura Navalis Mercatoria &c.* (Treatise on Shipbuilding, with Explanations and Demonstrations Respecting the *Architectura Navalis Mercatoria*, etc.). Stockholm: Johan Pfeffer, 1775. Partial English translation with commentary in *Architectura Navalis Mercatoria*. New York: Praeger, 1968.

Chapman, Fredrik Henrik af. "Om rätta sättet, att finna belägenhen av ett skepps centrum i gravitatis i höjden när det är liggande i vattnet med eller utan, sin fulla armering: Då man har den ritning varefter skeppet är byggt" (On the Correct Method of Calculating a Ship's Center of Gravity When It Is Afloat, with or Without Its Complete Armament, When the Construction Drawings Are Available). *KVAH* (1787), 48–53.

Chapman, Fredrik Henrik af. "Physiska rön, om det motstånd, kroppar lida, som föras rütt fram genom vatnet" (Physical Observations of the Resistance Experienced by Bodies When They Are Moved Through the Water). *KVAH* (1795), 73–126. Reprinted as *Physiska rön, om det motstånd, kroppar lida, som föras rütt fram genom vatnet*. Stockholm: Lars Salvius, 1795.

Chapman, Fredrik Henrik af. *Försök till en theoretisk afhandling att gifwa åt linie-skepp deras rätta storlek och form, likaledes för fregatter och bevärade fartyg* (Theoretical Treatise to Give Ships of the Line Their Proper Size and Form, Likewise for Frigates and Smaller Craft). Carlskrona: Kongliga Boktryckeriet, 1806.

Chauchot. *Sur les Mouvements de roulis et tangage des navires* (On the Movements of Rolling and Pitching of Ships). Paris: Martin, Guérin, et al., 1755.

Chauchot. Personal dossier, ANF, Fonds Marine C2, "Chauchot" (no date).

Chevillard, Jean-Denis (cadet), and François Guillaume Clairan-Deslauriers. Letter to Duhamel du Monceau regarding a 64-gun vessel. PEM, collection Duhamel du Monceau, MH 25, box 2, folder 6, item 10.1 (Rochefort, 4 December 1765).

Choiseul, Étienne François, duke of. *Ordonnance du roi concernant la marine, du 25 mars 1765* (King's Ordinance Concerning the Navy, of 25 March 1765). Paris: Imprimerie Royale, 1765.

Clairin-Deslauriers, François Guillaume. Letter to Duhamel du Monceau on inclining of *Intrépide*. PEM, collection Duhamel du Monceau, MH 25, box 2, folder 2, item 4.8 (Brest, 8 May 1748).

Clairaut, Alexis. *Théorie de la figure de la terre, tirée des principes de l'hydrostatique* (Theory of the Shape of the Earth, Derived from Hydrostatic Principles). Paris: David Fils, 1743.

Clairaut, Alexis. "Nouvelle Solution des quelques problèmes sur la manoeuvre des vaisseaux" (New Solutions to Some Problems on the Maneuvering of Vessels). *HMAS* (1760), pp. 171–178.

Clément, Pierre. *Lettres, instructions et mémoires de Colbert* (Letters, instructions and memoirs of Colbert). Paris: Imprimerie Impériale, 1864.

Colbert, Jean-Baptiste. Letter to intendants Arnoul, Demuyn, and Seuil on the need for a theory of ships. ANF, Fonds Marine, B2/39/464 (Fontainebleau, 10 September 1678). Printed in Clément, *Lettres, instructions et mémoires de Colbert* (1864), vol. 3, pp. 535–536; and Lemineur. *Les Vaisseaux du Roi Soleil* (1996), p. 215.

Colbert, Jean-Baptiste. Letter to Abraham Duquesne, inviting him to develop a theory of construction. ANF, Fonds Marine, B2/39/515 (Versailles, 12 October 1678). Excerpted in Leminuer, *Les Vaisseaux du Roi Soleil* (1996), p. 216.

Cochot. “Calcul d’un vaisseau de 60 canons” (Calculation of a 60-Gun Vessel), letter to Duhamel du Monceau. PEM, collection Duhamel du Monceau, MH 25, box 2, folder 7, item 11.2 (Paris, January 1754).

Condorcet, Marie Jean Antoine Nicolas de Caritat, marquis of. “Éloge de M. de La Condamine” (Eulogy of M. de La Condamine). *HMAS* (1774), pp. 85–112.

Condorcet, Marie Jean Antoine Nicolas de Caritat, marquis of. “Éloge de M. le Comte de Maurepas” (Eulogy of the Count of Maurepas). *HMAS* (1781), pp. 79–102.

Craig, John. “Epistola ad Editorem Continens Solutionum Duorum Problemstum” (Letter to the Editor Containing the Solutions to Two Problems). *PTRS* (1700/1701), pp. 746–751.

Crescentio, Bartolomeo Romano. *Nautica Mediterranea* (Mediterranean Navigation). Rome: Bonfadino, 1602.

Croissy, Charles Colbert, marquis of. “Mémoire sur la marine d’Angleterre” (Memoir on the Navy of England). ANF, Fonds Marine, B/7/474, Marine Anglaise, piece 9 (1672, but dated 1689).

D’Alembert, Jean Le Rond. *Traité de dynamique* (Treatise on Dynamics). Paris: David, 1743; 1758. Reprinted Paris: Éditions Jacques Gabay, 1990.

D’Alembert, Jean Le Rond. *Traité de l’équilibre et du mouvement des fluids: Pour servir de suite au Traité de dynamique* (Treatise on the Equilibrium and Movement of Fluids, to Serve as the Sequel to the *Treatise on Dynamics*). Paris: David, 1744; 1770.

D’Alembert, Jean Le Rond. *Essai d’une nouvelle théorie de la résistance des fluides* (Essay on a New Theory of the Resistance of Fluids). Paris: David, 1752.

Dassié, Charles. *L’Architecture navale, contenant la manière de construire les navires, galères et chaloupes, et la définition de plusieurs autres espèces de vaisseaux* (Naval Architecture, Containing the Manner of Constructing Ships, Galleys and Longboats, & the Definition of Many Other Types of Vessels). Paris: Jean de la Caille, 1677; Paris: Laurent d’Houry, 1695. Facsimile, Nice: Ancre, 1994.

Deane, Anthony. “Doctrine of Naval Architecture.” Pepys Library, Magdalene College, Cambridge University, manuscript 2910 (undated, ca. 1670). Printed in *Deane’s Doctrine of Naval Architecture 1670*, edited by Brian Lavery. London: Conway Maritime Press, 1981.

Deane, Anthony. "Method of Measuring the Body of a Ship and Pre-calculating Its Draught of Water." Pepys Library, Magdalene College, Cambridge University, manuscript 2501 (undated, ca. 1670).

Dee, John. *The Mathematicall Praeface to the Elements of Geometrie of Euclid of Megara*. London; John Daye (1570). Facsimile, New York: Science History Publications, 1975.

Descartes, René. *Discours de la méthode pour bien conduire sa raison: Et chercher la vérité dans les sciences* (Discourse on the Method for Rightly Conducting Reason: and for Searching for the Truth in Science). Leyden: Jean Maire, 1637.

Descartes, René. *Principia Philosophiae* (Principles of Philosophy). Amsterdam: Elzevirium, 1644.

Deslandes, André-François Boureau. "Lettre écrite à M. de C. sur la construction des vaisseaux." *JT* (1747), pp. 2055–2067. (Anonymous letter, attributed in secondary sources to Deslandes.)

Deslandes, André-François Boureau. "Seconde Lettre écrite à M. de C. sur la construction des vaisseaux." *JT* (1748), pp. 418–435. (Anonymous letter, attributed in secondary sources to Deslandes.)

Digges, Thomas, and Leonard Digges. *An Arithematicall Militare Treatise Named "Stratiticos"*. London: Bynneman, 1579.

Dryden, John. *The Poems of John Dryden*, edited by John Sargeant. London: Oxford University Press, 1935.

Du Buat, Pierre Louis Georges. *Principes d'hydraulique* (Principles of Hydraulics), 2 vols. Paris: Imprimerie de Monsieur, 1779.

Ducrest, Charles Louis, marquis of. *Essais sur les machines hydrauliques* (Trials on Hydraulic Machines). Paris: Esprit, 1777.

Ducrest, Charles Louis, marquis of. *Notice de l'expérience faite à Copenhague pour le compte de MM. de Coninck d'un vaisseau construit en planches et de plusieurs autres découvertes d'une haute importance, toutes relatives à la navigation* (Notice of the Experiment Done in Copenhagen for the Account of M. de Coninck, on a Vessel Constructed of Boards and of Several Other Discoveries of Great Importance, All Relative to Navigation). Copenhagen: Seidelin, 1799.

Ducrest, Charles Louis, marquis of. *Nouvelle Théorie de la construction des vaisseaux* (New Theory on the Construction of Vessels). Copenhagen: Seidelin, 1799.

Dudley, Robert. *Dell'arcano del mare* (Of the Secrets of the Sea). Florence: Onofri, 1646; 1661.

Du Hamel, Jean-Baptiste. "Invention de M. Renault." *PVAS* (3 May 1681), p. 99. Reprinted in *HMAS* (1681), p. 330.

Duhamel du Monceau, Henri-Louis. "Rapport de Duhamel du Monceau sur la petite école de marine qu'il dirige à Paris" (Report of Duhamel du Monceau on the Little Navy School That He Directs in Paris). ANF, Fonds Marine, G/89/3, folio 118 (Paris, June 1749).

Duhamel du Monceau, Henri-Louis. *Éléments de l'architecture navale, ou Traité pratique de la construction des vaisseaux* (Elements of Naval Architecture, or Practical Treatise of the Construction of Vessels). Paris: Charles-Antoine Jombert, 1752; 2nd ed., 1758. Facsimile, Nice: Éditions Omega, 1994. Translated by Christian Gottlieb Daniel Müller as *Anfangsgründe der Schiffbaukunst aus dem Französischen des Herrn Henri Louis Duhamel du Monceau* (Elements of Shipbuilding, from the French of Mr. Henri Louis Duhamel du Monceau). Berlin: Pauli, 1791. Facsimile by Horst Hamecher. Nandruck: Verlag Kassel, 1973.

Duhamel du Monceau, Henri-Louis. "État des services de M. Duhamel de l'Académie Royale des Sciences, inspecteur de la marine (Statement of Services of M. Duhamel of the Royal Academy of Sciences, Inspector of the Navy). ANF, Fonds Marine, C/7/93 (Paris, 13 September 1774).

Dupin, Charles. *Développements de géométrie, avec des applications à la stabilité des vaisseaux, aux déblais et remblais, au défilement, à l'optique, etc. . . . pour faire suite à la Géométrie descriptive et la Géométrie analytique de M. Monge* (Developments in Geometry; with Applications to the Stability of Vessels, to Trenches and Embankments, to Ramparts, to Optics, etc. Following the *Descriptive Geometry* and *Analytic Geometry* of M. Monge). Paris: V. Courcier, 1813.

Elvius, Pehr. "Undersökning huru vida jämnvigtspunctens belägenhet kan göra et skepp lättare eller svårare, at segla snedt för vinden" (Investigation of How the Position of the Center of Equilibrium Can Make a Ship More or Less Easy to Sail on the Wind Close-hauled). *KVAH* (1747), pp. 226–230.

Elvius, Pehr. "Vetenskapernas historia om mekanismen uti skeppens fart, och den underrättelse man deraf hafver håmtat, för skeppens byggnad och styrande" (History of Science Regarding the Mechanisms Involved in the Speed of Ships and What We Have Learned from Them as Regards the Building and Steering of Ships). *KVAH* (1747), pp. 243–250.

Emerson, William. "The Construction of the Fore Part of a Ship That Will Move Through the Water with the Least Possible Resistance." In *A Collection of Papers on Naval Architecture: Originally Communicated Through the Wrapper of the European Magazine*, edited by John Sewell, pp. 39–41. London: Sewell, 1800.

Euler, Johann Albrecht. "Recherches sur l'arrimage des vaisseaux, et quelles bonnes qualités on en peut procurer à un vaisseau" (Research on the Lading of Vessels, and the Good Qualities It Can Bring to a Vessel), 1761 prize. *RPRP*, 7 (1769). Reprinted as *Recherches sur l'arrimage des vaisseaux, et quelles bonnes qualités on en peut procurer à un vaisseau*. Paris: Gaurin et Delatour, 1769. Reprinted with commentary in Euler, *Opera Omnia*, 2nd ser., vol. 21 (1978).

Euler, Leonhard. "Meditationes super Problemate Nautico, de Implantatione Malorum, Quae Proxima Accessere ad Praemium Anno 1727" (Thoughts on the Naval Problem of Positioning of Masts, Which Took Second Place for the Prize of the Year 1727), 1727 prize submission. *RPRP*, 2 (1752). Reprinted in Bouguer, *De la Mâturation des vaisseaux*. Paris: Claude Jombert, 1728. Reprinted with commentary in Euler, *Opera Omnia*, 2nd ser., vol. 20 (1974), pp. 1–35.

Euler, Leonhard. "Judicium de Libello Domini de La Croix ex Gallia huc Transmisso" (Review of the Booklet by M. de La Croix from France Submitted Here) (2 September 1735) and "Notae ad

Responsiones Viri Illustris de La Croix Factae ab L. Euler" (Notes on the Response by the Famous M. de La Croix Made by L. Euler) (3 September 1736). Reprinted in Euler, *Opera Omnia*, 2nd ser., volume 18 (1967), pp. 413–427.

Euler, Leonhard. *Scientia Navalis, seu Tractatus de Construendis ac Dirigendis Navibus Pars Prior Complectens Theoriam Universam de Situ ac Motu Corporum Aquae Innatantium* (Naval Science, or Treatise of the Construction and Operating of Ships, the First Part Including a Collection of General Theorems About the Position and Motion of a Body Floating in Water). Saint Petersburg: Academy of Sciences, 1749). Reprinted with commentary in Euler, *Opera Omnia*, 2nd ser., vol. 18 (1967), and vol. 19 (1972).

Euler, Leonhard. "Principes généraux de l'état de l'équilibre des fluides" (General Principles of the State of Equilibrium of Fluids). *HASB* (1755), pp. 217–273; "Principes généraux du mouvement des fluides" (General Principles of Movement of Fluids)," *ibid.*, pp. 274–315; and "Continuation des recherches sur la théorie du mouvement des fluides" (Continuation of Research on the Theory of Movement of Fluids)," *ibid.*, pp. 316–361. The three memoirs are reprinted with commentary in Euler, *Opera Omnia*, 2nd ser., volume 12 (1954), pp. 2–132.

Euler, Leonhard. "Principia Motus Fluidorum" (Principles of the Motion of Fluids)." *NCP*, 6 (1756/1757), pp. 271–311. Reprinted with commentary in Euler, *Opera Omnia*, 2nd ser., vol. 12 (1954), pp. 133–168.

Euler, Leonhard. "Examen des efforts qu'ont à soutenir toutes les parties d'un vaisseau dans le roulis et dans le tangage" (Examination of the Forces That All Parts of a Vessel Must Support in Roll and Pitch), 1759 prize. *RPRP*, 8 (1771). Reprinted as *Examen des efforts qu'ont à soutenir toutes les parties d'un vaisseau dans le roulis et dans le tangage*. Paris: Gêurin et Delatour, 1771. Reprinted with commentary in Euler, *Opera Omnia*, 2nd ser., vol. 21 (1978), pp. 1–30.

Euler, Leonhard. *Théorie complete [sic] de la construction et de la manoeuvre des vaisseaux, mise à la portée de ceux qui s'appliquent à la navigation* (Complete Theory of the Construction and Maneuvering of Vessels, Put at the Disposal of Those Involved in Navigation). Saint Petersburg: Academy of Sciences, 1773. Reprinted with commentary in Euler, *Opera Omnia*, 2nd ser., vol. 21 (1978), pp. 80–222. Unauthorized edition, *Théorie complète de la construction et de la manoeuvre des vaisseaux*. Paris: Charles-Antoine Jombert, 1776. Translated by Henry Watson as *A Compleat Theory of the Construction and Properties of Vessels, with Practical Conclusions for the Management of Ships, Made Easy to Navigators*. London: Elmsley, 1776.

Euler, Leonhard. "Essai d'une théorie de la résistance qu'éprouve la proue d'un vaisseau dans son mouvement" (Attempt at a Theory of Resistance Encountered by the Bow of a Vessel in its Motion). *HMAS* (1778), pp. 597–602. Reprinted in Euler, *Opera Omnia*, 2nd ser., vol. 21 (1978), pp. 223–229.

Euler, Leonhard. *Leonhardi Euleri Opera Omnia* (Leonhard Euler's Complete Works). Leipzig, Bern, Basel, and Zurich, Birlchäuser 1911–. [101 volumes to date]

Fatio de Duillier, Nicolas. *Lineae Brevissimi Descensus Investigatio Geometrica Duplex, Cui Addita Est Investigatio Geometrica Solidi Rotundi in Quod Minima Fiat Resistentia* (Geometrical Investigation of

the Line of Quickest Descent, to Which Is Added: Geometrical Investigation of the Round Solid Which Demonstrates Least Resistance). London: Everingham and Taylor, 1699.

Fatio de Duillier, Nicolas. "Excerpta ex Responsione Dn Nic. Fatii Duillierii ad Excerpta ex Literis Dn Joh. Bernoulli" (Excerpt from the Response of Fatio Duillier to the Excerpt from the Letter of Johann Bernoulli). *AE* (1701), pp. 134–136.

Fatio de Duillier, Nicolas. "Epistola Nicolai Fatij, Reg Soc. Lond. Sod. ad Fratrem Joh. Christoph. Facium Dictae Societatis Sodalem, Qua Vendicat Solutionem Suam Problematis de Inveniendō Solido Rotundo seu Tereti in Quod Minima Fiat Resistentia" (Letter of Nicolas Fatio, Royal Society of London, to His Brother Jean Christophe, who Confirmed His Solution to the Problem of Finding the Round or Smooth Solid in Which Resistance Is Minimum). *PTRS* (1714), pp. 172–176.

Fontenelle, Bernard le Bouyer de. "Éloge de M. Renau" (Eulogy of Mr. Renau). *HMAS* (1719), pp. 101–120.

Fontenelle, Bernard le Bouyer de. "Sur le Jaugeage des vaisseaux" (On the Admeasurement of Vessels). *HMAS* (1721), pp. 43–51.

Forfait, Pierre Alexandre Laurence. *Traité élémentaire de la mâtire des vaisseaux, à l'usage des élèves de la marine* (Elementary Treatise on the Mastings of Vessels for the Use by Students of the Navy). Paris: Clousier, 1788.

Fournier, Georges. *Hydrographie, contenant la theorie et la pratique de toutes les parties de la navigation* (Hydrography, Containing the Theory and Practice of All Parts of Navigation). Paris: Soly, 1643; 2nd ed., Paris: Dupuis, 1667. Reprint, Grenoble: Éditions des 4 Seigneurs, 1973.

Franklin, Benjamin. "Letter to Sir John Pringle 10 May 1768." In Franklin's *Experiments and Observations on Electricity: Made in Philadelphia in America*. London: David Henry, 1769. Reprinted in *The Papers of Benjamin Franklin*, vol. 15, edited by William Willcox. New Haven, CT: Yale University Press, 1972.

Furttenbach, Joseph. *Architectura Navalis* (Naval Architecture). Ulm: Jonam Saur, 1629. Reprinted Hildesheim: Olms, 1975.

Fuss, Nicolas. "Éloge de M. Léonhard Euler" (Eulogy of Mr. Leonhard Euler). *NAP* (1783), 159–212.

García de Palacio, Diego. *Nautical Instruction 1587*, translated by J. Bankston. Bisbee, AZ: Terrate Associates, 1986.

Gautier, Jean-François. "De l'Arrimage des vaisseaux" (On the Lading of Vessels), 1765 prize submission. *RPRP*, 9 (1777).

Gay, Pierre de. *Mémoire sur la forme de la carène des vaisseaux, ou Exposition très succincte d'un nouveau système de construction, suivie de quelques mots sur la force matérielle de l'armée navale* (Memoir on the Hull Form of Vessels, or Very Succinct Exposition of a New System of Constrction, Followed by a Few Words on the Material Force of the Navy). Paris: Desenne, 1792.

Geslain, Blaise. "Extrait des ouvrages qui ont esté le sujet de mon séjour en Angleterre et de ceux dont j'ay rendu compte" (Extract of the Works Which Are the Subject of My Stay in England and of Which I Have Given an Account). Cornell University Library, Division of Rare and Manuscript Collections, Maurepas Collection, box 9, folder 4 (Versailles, 10 July 1732).

Grandjean de Fouchy, Jean-Paul. Examination of proposal of M. de La Croix. *PVAS* (9 February 1735), p. 31.

Grandjean de Fouchy, Jean-Paul. "Éloge de M. Bouguer" (Eulogy of Mr. Bouguer). *HMAS* (1758), pp. 127–136.

Griffiths, John Willis. *Treatise on Marine and Naval Architecture; or, Theory and Practice Blended in Ship Building*. New York: Pudney & Russell, 1850.

Groignard, Antoine. "Mémoire sur une nouvelle façon de terminer l'avant des vaisseaux plus solide, moins sujette a pourrir, plus susceptible de radoub et plus géométrique que celle d'ont on se sert" (Memoir on a New Way of Making the Bow of Vessels More Solid, Less Subject to Rotting, Easier to Refit and More Geometric Than Is Currently Used). Sent to Minister of the Navy Rouillé de Jouy. ANF, Fonds Marine, D/1/11 (19 April 1754).

Groignard, Antoine. "Mémoire composé à l'occasion du prix proposé par l'Académie Royale des Sciences, dont le sujet est: L'examen des efforts qu'ont à soutenir toutes les parties de vaisseau dans le roulis et dans le tangage, et la meilleure manière de procurer à leur assemblage la solidité nécessaire pour résister à ces efforts, sans préjudicier aux autres bonnes qualités du vaisseau" (Memoir Composed for the Event of the Prize Proposed by the Royal Academy of Sciences, of Which the Subject Is: The Examination of Forces That All Parts of the Vessel Must Support in Rolling and Pitching, and the Best Way to Give the Framework the Necessary Strength to Sustain These Forces, Without Harming Other Good Qualities of the Vessel). 1755 prize submittal, 1759 prize. *RPRP*, 7 (1764).

Groignard, Antoine. "De l'Arrimage des vaisseaux" (On the Lading of Vessels), 1765 prize submittal. *RPRP*, 9 (1777). Reprinted in Bossut: *Traité de l'arrimage des vaisseaux* (1810); and in Bourdê de Villehuet, *Le Manœuvrier* (Paris: Bachelier, 1814; 1832), pp. 351–382.

Hällström, Gustaf Gabriel. "Försök till en avhandling om solidum minime resistance i anledning av Nordmarkske grundformlerna, rörande vattnets motstånd" (Attempt at a Treatise on the Solid of Least Resistance, Based on Nordmark's Basic Formulas on the Resistance of Water). *KVAH* (1808), pp. 159–193.

Harris, G. G., ed. *Trinity House of Deptford Transactions, 1609–35*. London: London Record Society, 1983.

Hayes, Charles. *Treatise of Fluxions; or an Introduction to Mathematical Philosophy*. London: Edward Midwinter, 1704.

Hennert, Johann Friedrich. *Cursus Matheseos Adplicatae* (Applied Mathematics Course), part 6, "Elementa Architectura Navalis, Artis Gubernandi Navis, Pyrotechnicae et Acusticae" (Elements of Naval Architecture, Maneuevering of Ships, Pyrotechnics and Acoustics). Utrecht: Trajectae ad Rhenum, 1775.

Hermann, Jacob. *Phoronomia, sive de Viribus et Motibus Corporum Solidorum et Fluidorum* (Rational Mechanics, or the Force and Motion of Solid and Fluid Bodies). Amsterdam: Wetstenios, 1716.

Herreshoff, Halsey C. "Hydrodynamics and Aerodynamics of the Sailing Yacht." *TSNAME* (1964), vol. 72, pp. 445–492.

Hoste, Paul. *Traité des évolutions navales, composé sur les mémoires de Monsieur le comte de Tourville, vice-amiral de France* (Treatise on Naval Evolutions, Composed on the Memoirs of the Count of Tourville, Vice Admiral of France). SHDMV, cote SH, ms 115 (1691).

Hoste, Paul. *Recueil des traités de mathématique: Qui peuvent estre nécessaires à un gentilhomme, pour servir par mer ou par terre* (Collection of Mathematics Treatises: Which Can Be Necessary to a Gentleman, to Serve on Sea or on Land). Lyon: Anisson, 1692.

Hoste, Paul. *L'Art des armées navales ou Traité des évolutions navales* (The Art of Naval Armies or Treatise of Naval Evolutions). Lyon: Anisson & Posuel, 1697.

Hoste, Paul. "Théorie de la construction des vaisseaux" (Theory of the Construction of Vessels). Appended to his *L'Art des armées navales*. Lyon: Anisson & Posuel, 1697.

Hoste, Paul. "Architecture navale, ou pratique de la construction des vaisseaux, copié sur les mémoires du P. Paul Hôte, Jésuite" (Naval Architecture, or Practice of the Construction of Vessels, Copied from the Memoirs of Father Paul Hoste, Jesuit), copied by Jean Baptiste Thioly. SHDMV, cote SHM, ms.138 (1714).

Huygens, Christiaan. "De Iis Quae Liquido Supernatant Libri Tres" (Three Books on Bodies Floating on Top of a Liquid) (1650). In Huygens, *Oeuvres complètes*, vol. 11 (1908), pp. 85–210.

Huygens, Christiaan. "Résistances éprouvées par des surfaces (Resistance shown by surfaces)" (22 April 1691). In Huygens, *Oeuvres complètes*, vol. 21 (1950), pp. 335–341.

Huygens, Christiaan. "Remarque de M. Huguens sur le livre de la *Manoeuvre des vaisseaux* imprimé à Paris en 1689" (Remark by Mr. Huygens on the Book of Ship Maneuvering printed in Paris in 1689). *Bibliothèque universelle* (September 1693), pp. 195–202. Reprinted in Huygens, *Oeuvres complètes*, vol. 10 (1905), pp. 525–531.

Huygens, Christiaan. "Réplique de Mr. Huguens à la reponse de Mr. Renau, ingénieur général de la marine en France" (Reply of Mr. Huygens to Mr. Renau, Engineer General of the French Navy). *Histoire des ouvrages des sçavans* (April 1694), 388–392. Reprinted in Huygens, *Oeuvres complètes*, vol. 10 (1905), pp. 654–658.

Huygens, Christiaan. "Raisons qu'a M. Huguens pour se plus continuer la dispute avec M. Renau touchant la theorie de la manouevre des vaisseaux" (Reasons That Mr. Huygens Has for Continuing the Dispute with Mr. Renau, Touching on the Theory of the Maneuvering of Vessels). *Histoire des ouvrages des sçavans* (November 1694), pp. 128–129. Reprinted in Huygens, *Oeuvres complètes*, vol. 10 (1905), pp. 694–695.

Huygens, Christiaan. *Oeuvres complètes de Christiaan Huygens* (Complete Works of Christiaan Huygens), 21 vols. The Hague: Martinus Nijhoff, 1888–1950.

Jefferson, Thomas. "Description of a Mould-board of Least Resistance and of the Easiest and Most Certain Construction." *Transactions of the American Philosophical Society* (1799), 313–322.

Jefferson, Thomas. *Political Writings*, edited by Joyce Appleby and Terence Ball. Cambridge: Cambridge University Press, 1999.

Joint Doctrine Division, U.S. Department of Defense. *Joint Publication 1-02, DOD Dictionary of Military and Associated Terms*. <http://www.dtic.mil/doctrine/jel/doddic>. Amended through June 2003. Accessed July 2003.

Juan y Santacilia, Jorge. *Examen marítimo, teórico práctico, ó Tratado de mecánica aplicado á la construcción, conocimiento y manejo de los navios y demás embarcaciones* (Maritime Examination, Theoretical and Practical, or Treatise of Mechanics Applied to the Construction, Design and Handling of Ships and Boats), 2 vols. Madrid: Manuel de Mena, 1771. Facsimile, Madrid: Instituto de España, 1968. Facsimile of vol. 2, Madrid: Colegio Oficial de Ingenieros Navales, 1992. Vol. 1, rev. ed. by Gabriel Ciscar y Ciscar. Madrid: Imprenta Real, 1793. Translated by Pierre Lévêque as *Examen maritime, théorique et pratique*. Nantes: Malassis & Despillay, 1783.

Juan y Santacilia, Jorge, and Antonio de Ulloa y de la Torre-Guiral. *A Voyage to South America*, abridged translation by John Adams. New York: Knopf, 1964.

Juan y Santacilia, Jorge, and Antonio de Ulloa y de la Torre-Guiral. *Discourse and Political Reflections on the Kingdoms of Peru*, edited by John J. TePaske. Norman: University of Oklahoma Press, 1978.

Laberthonie, Pierre-Thomas. *Relation de la conversion et la mort de M. Bouguer* (Account of the Conversion and Death of Mr. Bouguer). Paris: Mequignon, 1784.

La Condamine, Charles-Marie de. *Lettre de Monsieur de La Condamine à M. •• sur le sort des astronomes qui ont eu part aux dernières mesures de la terre, depuis 1735* (Letter from M. de La Condamine to Mr. X on the Fate of the Astronomers Who Took Part in the Latest Measures of the Earth, Since 1735). (Paris, 1773).

La Croix, César Marie de. "Mémoire sur la nécessité de pourvoir à la disette et à la foiblesse des ouvriers des ateliers, et sur les moyens d'y remédier" (Memoir on the Necessity of Attending to Food Shortages and to the Feebleness of Workers in Shops, and on the Means of Redressing the Situation) (1719). ANF Fonds Marine G121. Printed in *Gérer et comprendre, série des Annales des mines* (Manage and Understand, series of the Annals of Mines), no. 42 (February 1996), pp. 36–40.

La Croix, César Marie de. Letter to Minister of the Navy Maurepas regarding problems with *Lys*. Cornell University Library, Maurepas collection, box 9, folder 3 (25 March 1732).

La Croix, César Marie de. "Extrait du mécanisme des mouvemens des corps flottants" (Extract from the Mechanism of Movements of Floating Bodies). *JT* (1735), pp. 638–668. Reprinted as *Extrait du mécanisme des mouvemens des corps flotans* Paris: Chaubert, (1735); and "Éclaircissements sur l'extrait du mécanisme des mouvemens des corps flottants" (Explanations of the Extract from the Mechanism of Movements of Floating Bodies). *JT* (1736), pp. 773–863. Reprinted as *Éclaircissements sur l'extrait du mécanisme des mouvemens des corps flotans* (Paris: Robustel, 1736).

Both works translated by Charles Knowles as *Abstract on the Mechanism of the Motion of Floating Bodies*. London: Robson, 1746; 1775.

La Croix, César Marie de. Letter to Minister of the Navy Maurepas requesting a promotion. Cornell University Library, Maurepas Collection, box 7, folder 9 (1747). Commentary in *Historical French Documents of the Eighteenth Century*. New York, Parolce-Bernet Collierie, Inc. (1962), pp. 11–12.

Lagrange, Joseph-Louis. “Mémoire sur la théorie du mouvement des fluides” (Memoir on the Theory of Movement of Fluids). *HASB* (1781), pp. 151–198.

Lagrange, Joseph-Louis. *Mécanique analytique* (Analytical Mechanics). Paris: La Veuve Desaint, 1788.

La Roque, Jean-Paul de. Review of *De la théorie de la manoeuvre des vaisseaux* (On the Theory of the Maneuvering of Vessels). *JS* (12 December 1689), pp. 745–748.

Le Monnier, Pierre Charles. Letters to Minister of the Navy Choiseul on the inclining of *Royal Louis*. ANF, Fonds Marine, D/1/13, folios 59–63 (Brest, January 1763–January 1764).

Lévêque, Pierre. Letter to Minister of the Navy Sartines on translation of *Examen maritime*. ANF, Fonds Marine, D/1/25, piece 22 (Nantes, 9 October 1779).

L'Hôpital, Guillaume-François-Antoine, marquis of. “Méthode facile pour trouver un solide rond, qui étant mu dans un fluide en repos parallèlement à son axe, rencontre moins de résistance que tout autre solide, qui ayant même longueur et largeur, se meuve avec la même vitesse suivant la même direction” (Easy Method to Find a Round Solid, Which Being Moved in a Still Fluid Parallel to Its Own Axis, Encounters Less Resistance Than Any Other Solid Having the Same Length and Width, Moving with the Same Speed Following the Same Direction). *HMAS* (1699), pp. 107–112.

L'Hôpital, Guillaume-François-Antoine, marquis of. “Facilis et Expedita Methodus Inveniendi Solidi Rotundi” (Easy and Expeditious Method to Find a Round Solid). *AE* (1699), pp. 354–359. Reprinted in Johann Bernoulli: *Opera Omnia*, edited by J. E. Hofman, vol. 1, pp. 311–315. Hildesheim: G. Olms, 1968.

MacLaurin, Colin. *A Treatise on Fluxions*, 2 vols. Edinburgh: Ruddimans, 1742.

Mairan, Jean-Jacques d'Ortous de. “Remarques sur le jaugeage des navires” (Remarks on the Admeasurement of Ships). *HMAS* (1721), pp. 76–106.

Mairan, Jean-Jacques d'Ortous de. “Instruction abrégée et méthode pour le jaugeage des navires” (Abridged Instruction and Method for Admeasurement of Ships). *HMAS* (1724), pp. 227–240.

Mairan, Jean-Jacques d'Ortous de. Reception of Bouguer's treatise on masting. *PVAS* (1 February 1724), p. 51.

Mairan, Jean-Jacques d'Ortous de. Remarks on Bouguer's treatise, titled “L'Art de mâter les vaisseaux 1^{re} partie” (The Art of Masting Vessels 1st Part). *PVAS* (23 August 1724), pp. 291–295.

Mairan, Jean-Jacques d'Ortous de. "Lettre de M. de Mairan à M. l'Abbé Bignon à Meulan, du 20 Avril 1727. Sur le livre de M. Bouguer, De la Mâtüre des vaisseaux" (Letter from Mr. de Mairan to the Abbot Bignon at Meulan, 20 April 1727. On the book of Mr. Bouguer, *On the Masting of Vessels*). *JS* (1728), pp. 432–437.

Maitz de Goimpy, François Louis Edmé Gabriel, count of. *Traité sur la construction des vaisseaux* (Treatise on the Construction of Vessels). Paris: Couturier, 1776.

Marguerie, Jean-Jacques de. "Sur l'Établissement d'une nouvelle théorie de la résistance de fluids par l'expérience" (On the Establishment of a New Theory of Resistance of Fluids by Experiment). *Mémoires de l'Académie Royale de Marine* (Memoirs of the Royal Academy of Navy), pp. 102–141. Brest: Malassis, 1773.

Mariotte, Edmé. *Traité du mouvement des eaux et des autres corps fluides* (Treatise on the Movement of Water and Other Fluid Bodies), edited by Philippe de La Hire. Paris: Estienne Michallet, 1686.

Maupertuis, Pierre-Louis Moreau de. "Sur les Coubres de poursuite" (On Pursuit Curves). *HMAS* (1732), pp. 15–16.

Maurepas Collection. Cornell University Library, Division of Rare and Manuscript Collections. Description at <http://rmc.library.cornell.edu/frenchrev/Maurepas/default.html>. Full description in *Historical French Documents of the Eighteenth Century: From the Archives of Jean-Frédéric Phélypeaux Comte de Maurepas (1701–1781)*. New York: Parke-Bernet Galleries, 1962.

Mencke, Otto. Review of *La Théorie de la manoeuvre des vaisseaux*. *AE* (August 1690), pp. 388–392.

Moitoret de Blainville, Antoine. *Traité du jauge de la marine et de la navigation* (Treatise of Marine and Navigational Admeasurement). Appended to his *Nouveau Traité du grand négoce de France* (New Treatise on the Principal Trade of France). Rouen: Jean Besongne, 1698.

Moivre, Abraham de. "Specimina Quaedam Illustria Doctrinae Fluxionum sive Exempla Quibus Methodi Istius Usus et Praestantia in solvendis problematis geomtricus elucidatur; ex Epistola Peritissimi Mathematici D. Ab. de Moivre Desumpta" (Exact Proof of the Famous Doctrine of Fluxions, or Examples Used to Solve the Clarifying Geometrical Problem; Derived from the Letter of Abraham de Moivre). *PTRS* (1695), pp. 52–57.

Morineau, Pierre. "Répertoire de construction" (Repertoire of Construction). ANF, Fonds Marine, G 246, 1752 (or 1751–1762). Printed Nice: Ancre, 2005.

Muller, John. *Appendix or Supplement to the Treatise of Artillery*. London: Millar, 1768.

Murray, Mungo A. *Treatise on Ship-building and Navigation*. London: Millar, 1754; 2nd ed., 1765.

Newton, Isaac. *The Principia: Mathematical Principles of Natural Philosophy* 1687, translated by I. Bernard Cohen and Anne Whitman. Berkeley: University of California Press, 1999.

Nicole, François, and Alexis Claude Clairaut. "Rapport suivant de l'ouvrage de Mr. Bouguer. (Report on the work of Mr. Bouguer)" *PVAS* (1745), pp. 132–139.

Nordmark, Zacharias. "Grundformler till en ny teori om flytande kroppars motstånd" (Basic Formula for a New Theory of Properties of Fluid Resistance). *KVAH* (1805), pp. 145–176. Translated as *Principes d'une nouvelle théorie de la résistance des fluides*. Saint Petersburg: Academy of Sciences, 1808.

Nystrom, John W. *A Treatise on Parabolic Construction of Ships and Other Marine Engineering Subjects*. Philadelphia: Lippincott, 1863.

Ollivier, Blaise. Letter to Minister of the Navy Maurepas regarding problems with *Lys*. Cornell University Library, Maurepas Collection, box 9, folder 2 (1732).

Ollivier, Blaise. *Traité de construction 1736* (Construction Treatise 1736), edited by Hubert Berti and Jean Boudriot. Nice: Éditions Omega, 1992.

Ollivier, Blaise. *Remarques sur la marine des anglois et hollandois* (Remarks on the English and Dutch Navies) *Service Historique de la Défense, département marine Brest*, m.68 (1737). Translated edited by David H. Roberts as *18th Century Shipbuilding: Remarks on the Navies of the English and Dutch*. Jean Boudriot Publications, Rotherfield, 1992.

Ollivier, Joseph. Letter to Duhamel du Monceau concerning promotion of Pierre Augustin La Mothe. PEM, Duhamel du Monceau collection, MH 25, box 2, folder 4, item 7.2 (Brest, 5 December 1765).

Onzembray (or Ons-en-Bray), Louis Léon Pajot, count of. "Machine pour connoître sur mer l'angle de la ligne du vent et de la quille du vaisseau; comme aussi l'angle du méridien de la boussole avec la quille, et l'angle du méridien de la boussole avec la ligne du vent" (Machine to Know at Sea the Angle of the Line of the Wind and the Keel of the Vessel; as Well as the Angle of Meridian of the Compass with the Keel, and the Angle of the Meridian of the Compass with the Line of Wind). *HMAS* (1731), pp. 236–240.

Pardies, Ignace-Gaston. *La Statique ou La Science des forces Mouvantes* (Statics, or the Science of Moving Forces). Paris, Mabre-Cramoisy, 1673.

Parent, Antoine. *Éléments de mécanique et de physique, où l'on donne géométriquement les principes du choc et des équilibres entre toutes sortes des corps* (Elements of Mechanics and Physics, Providing Geometric Principles of Shock and Equilibrium Between all Kinds of Bodies). Paris: Jean de Nully, 1700.

Parent, Antoine. *Recherches de mathématique et de physique* (Research in Mathematics and Physics), 3 vols. Paris: Delaulne, 1705.

Parent, Antoine. "Premier Problème de la manoeuvre" (First Problem of Maneuver). *JT* (1714), pp. 154–174.

Parent, Antoine. "Analyse d'un nouveau livre intitulé *Essay d'une nouvelle théorie de la manoeuvre des vaisseaux*, par J. Bernoulli" (Analysis of a New Book titled *Essay on a New Theory of the Maneuvering of Vessels* by J. Bernoulli). *JT* (1715), pp. 696–718.

Parent, Antoine. "Résolution de trois problèmes célèbres tentés par M. Bernoulli de Basle dans son *Essai d'une nouvelle théorie de la manoeuvre*, en 1714, et avoient été proposé par M. Le. C.

Renau l'année précédente à M. Parent" (Resolution of Three Famous Problems Set Out by M. Bernoulli in his *Essay on a New Theory of Maneuvering*, in 1714, and Which Had Been Proposed by Mr. Renau the Year Before to M. Parent). *JT* (1715), pp. 893–904.

Pascal, Blaise. *Traité de l'équilibre des liqueurs, et de la pesanteur de la masse de l'air* (Treatise on the Equilibrium of Liquids and on the Weight of the Mass of the Air). Paris: Guillaume Desprez, 1663. Translated by I. H. B. and A. G. H. Spiers in *The Physical Treatises of Pascal: The Equilibrium of Liquids and the Weight of the Mass of the Air*. New York: Columbia University Press, 1937; New York: Octagon Books, 1973.

Pepys, Samuel. *Samuel Pepys's Naval Minutes*, edited by J. R. Tanner. Publications of the Naval Records Society, vol. 60. London: The Society, 1926.

Pepys, Samuel. *Further Correspondence of Samuel Pepys*, edited by J. R. Tanner. London: Bell, 1929.

Pepys, Samuel. *The Diary of Samuel Pepys*, edited by Robert Latham and William Matthews. London: Bell, 1970–1983 (9 vol).

Pett, Phineas. *The Autobiography of Phineas Pett*, edited by William Gordon Perrin. Publications of the Naval Records Society, vol. 51. London: The Society, 1918.

Pezenas, Esprit. *La Théorie et la pratique du jaugeage des tonneaux, des navires et de leurs segments* (The Theory and Practice of Admeasuring Barrels, Ships and Their Segments). Avignon: Jean Aubert, 1773.

Pitot, Henri de. "Règles ou loix générales des impulsions obliques des fluids, contre une surface plane" (General Rules or Laws of Oblique Impulsions of Fluids, Against a Plane Surface). *HMAS* (1727), pp. 49–62.

Pitot, Henri de. *La Théorie de la manoeuvre des vaisseaux réduite en pratique ou les Principes et les règles pour naviguer le plus avantageusement qu'il est possible* (The Theory of the Maneuvering of Vessels Reduced to Practice, or the Principles and Rules for Navigating the most Advantageously Possible). Paris: Claude Jombert, 1731. Translated by Edmund Stone as *The Theory of the Working of Ships Applied to Practice*. London: Davis and Valliant, 1743.

Pitot, Henri de. "Description d'une machine pour mesurer la vitesse des eaux courantes, et le sillage des vaisseaux" (Description of a Machine to Measure the Speed of Running Waters and the Wake of Vessels). *HMAS* (1732), pp. 363–376.

Polhem (Polhammer), Christopher. "Ny method at pröfva lasten i et skep, til lagom styfhet och rankining" (New Method to Test the Lading of a Ship, for Best Stiffness and Easiness). *KVAH* (1743), pp. 270–275.

Poterat, Abraham-Christophe-Pierre, marquis of. *Théorie du navire* (Ship Theory). Paris: Didot, 1826.

Rålamb, Åke Classon. *Skeps byggerij eller adelig öfnings tionde tom* (Shipbuilding from Exercises for Young Noblemen Volume 10). Stockholm: Niclas Wankijfs Tryckerij, 1691. Facsimile, Malmö, A. B. Malmö Ljustrycksanstalt, 1943.

Renau d'Elizagaray, Bernard. "Mémoire sur les constructions des vaisseaux, dans lequel il y a une méthode pour en conduire les façons" (Memoir on the Construction of Vessels, in Which There Is a Method for Creating the Narrowing Lines). ANF, Fonds Marine, D1/10, folio 5 (1679).

Renau d'Elizagaray, Bernard. "Mémoire du Sr Renau sur les constructions" (Memoir of Sir Renau on Construction). Letter to Seignelay, ANF, Fonds Marine, D1/10, folios 22–25 (February 1684).

Renau d'Elizagaray, Bernard. "État des services de Renau" (State of Service of Renau). BNF, manuscrits Clairambault, vol. 887 (Marine I5), folio 62 (ca 1687). Printed in *Bulletin historique et philologique* (Historical and Philological Bulletin) (1888), 258–259.

Renau d'Elizagaray, Bernard. *De la Théorie de la manoeuvre des vaisseaux* (On the Theory of the Maneuvering of Vessels), edited by Joseph Sauveur. Paris: Estienne Michallet, 1689. Translated by John Senex as *The Theory of the Handling or Working of Ships at Sea*. London: J. Humphreys, 1699 (or 1705).

Renau d'Elizagaray, Bernard. "Réponse de M. Renau à M. Huguens (Response of Mr. Renau to Mr. Huygens). *Histoire des ouvrages des Sçavans* (16–24 May 1694), pp. 329–339. Reprinted in Huygens, *Oeuvres complètes*, vol. 10, pp. 588–596.

Renau d'Elizagaray, Bernard. "Mémoire où est démontré un principe de la mécanique des liqueurs dont on s'est servi dans la *Théorie de la manoeuvre des vaisseaux* et qui a été contesté par M. Huguens" (Memoir Wherein Is Demonstrated a Principle of the Mechanics of Liquids Which Served in the *Theory of Maneuvering of Vessels* and Which Was Contested by Mr. Huygens). (1712).

Renau d'Elizagaray, Bernard, and Christiaan Huygens. *Réplique de M. Huegens à la réponse de M. Renau, sur le principe de la théorie de la manoeuvre des vaisseaux. Et la réponse de M. Renau à la réplique de M. Huegens* (Reply of Mr. Huygens to the Response of Mr. Renau, on the Principles of the Theory of the Maneuvering of Vessels. And the Response of Mr. Renau to the Reply of Mr. Huygens). Paris: Estienne Michallet, 1694.

Reyneau, Charles René. *Analyse démontrée* (Analysis demonstrated), 2 vols. Paris: Quillau, 1708.

Robins, Benjamin. *New Principles of Gunnery*. London: J. Nourse, 1742. Reprinted in *Mathematical Tracts of the Late Benjamin Robins*, edited by James Wilson, 2 vols. London: J. Nourse, 1761.

Romme, Charles Nicolas. *L'Art de la marine* (Naval Arts). Paris: Barrois, 1787.

Russell, John Scott. Notebook 6. Imperial College London, Science Museum Archive Collection, MS 516/6. (19 June 1863).

Saint-Jacques de Silvabelle, Guillaume de. "Du Solide de la moindre résistance" (On the solid of least resistance). *Mémoires de mathématiques et physique présentés à l'Académie par divers savans* (Memoirs of Mathematics and Physics Presented to the [Paris] Academy [of Sciences] by Various Learned Members), 3 (1760), pp. 638–649.

Savérien, Alexandre. *Nouvelle Théorie de la manoeuvre des vaisseaux à la portée des pilotes* (New Theory of Maneuvering for the Use of Pilots). Paris: Charles-Antoine Jombert, 1746. Reprinted Paris: Chaubert, 1747.

Savérien, Alexandre. *La Mâtûre discutée et soumise à des nouvelles loix* (Masting Discussed and Submitted to New Laws). Paris: Chaubert, 1747.

Savérien, Alexandre. *L'Art de mesurer sur mer le sillage du vaisseau* (The Art of Measuring the Wake of a Vessel at Sea). Paris: Charles-Antoine Jombert, 1750.

SAWE (Society of Allied Weight Engineers). *Weight Control Technical Requirements for Surface Ships*, Recommended Practice no. 12, Rev. B (21 May 1997).

Segondat-Duverniet, Charles-Antoine. "Calcul de la résistance d'un vaisseau de 74 canons" (Calculation of Resistance of a 74-Gun Vessel). Letter to Duhamel du Monceau. PEM, Duhamel du Monceau collection, MH 25, box 2, folder 5, item 8.4 (Brest, 9 December 1766).

Seignelay, Jean-Baptiste Colbert, marquis of (unsigned). "Remarque sur la marine d'Hollande" (Remark on the Navy of Holland). ANF, Fonds Marine, B/7/477, folio 6 (1672).

Seignelay Jean-Baptiste Colbert, marquis of. Orders and dispatches concerning the Navy. *ANF Fonds Marine* B2/42–43 (1680).

Seignelay, Jean-Baptiste Colbert, marquis of. Letter to Abraham Duquesne on the need to develop rules of construction. ANF, Fonds Marine, B2/43/46 (Saint-Germain-en-Laye, 22 January 1680).

Seignelay, Jean-Baptiste Colbert, marquis of. Letter to Abraham Duquesne on the need to develop rules of construction. ANF, Fonds Marine, B2/43/91 (Saint-Germain-en-Laye, 12 February 1680). Excerpted in Leminuer, *Les Vaisseaux du Roi Soleil* (1996), p. 221.

Seignelay, Jean-Baptiste Colbert, marquis of. Letter to Tourville on the need to develop rules of construction. ANF, Fonds Marine, B2/43/277 (Saint-Germain-en-Laye, 6 June 1680).

Seignelay, Jean-Baptiste Colbert, marquis of. Letter to Intendant Demuyn requesting that Pangalo's model be brought to Versailles. ANF, Fonds Marine, B2/42/298 (Versailles, 1 September 1680).

Seignelay, Jean-Baptiste Colbert, marquis of. Letter to Pierre Chertemps, marquis of Seuil, intendant of Rochefort, instructing Hubac to come to construction conferences. ANF, Fonds Marine, B2/45/72, and BNF, Nouvelles Acquisitions Françaises, 9481, folio 272 (Saint-Germain-en-Laye, 23 February 1681). Excerpted in Leminuer, *Les Vaisseaux du Roi Soleil* (1996), p. 224.

Seignelay, Jean-Baptiste Colbert, marquis of. Letter to Pierre Chertemps, marquis of Seuil, announcing that the king is still waiting for Hubac to come to the construction conferences. ANF, Fonds Marine, B2/44/109 (Saint-Germain-en-Laye, 15 March 1681). Excerpted in Leminuer, *Les Vaisseaux du Roi Soleil* (1996), p. 224.

Seignelay, Jean-Baptiste Colbert, marquis of. Letter to Jean-Louis Girardin de Vauvré, intendant of Toulon, announcing the departure of Duquesne. ANF, Fonds Marine, B2/44/153 (Saint-Germain-en-Laye, 9 April 1681).

Seignelay, Jean-Baptiste Colbert, marquis of. Letter to Pierre Chertemps, marquis of Seuil, announcing the departure of Hubac. ANF, Fonds Marine, B2/44/174 (Saint-Germain-en-Laye, 14 April 1681). Excerpted in Leminuer, *Les Vaisseaux du Roi Soleil* (1996), p. 224.

Sewell, John. "On the Importance of the Study of Shipbuilding by Philosophical as Well as Practical Men." In *A Collection of Papers on Naval Architecture*, edited by John Sewell, pp. vi–viii. London: Sewell, 1791.

Sewell, John, ed. *A Collection of Papers on Naval Architecture*. London: Sewell, 1791, 1792, 1795, 1800.

Sheldon, Carl. "De Subversione Navium" (On the Overturning of Ships). Ph.D. dissertation, University of Uppsala, 1757.

Sheldon, Gilbert. "Om skeppens tyngd och rymd uti watnet" (On Ships' Weight and Volume in Water). *KVAH* (1741), pp. 168–178.

Sheldon, Gilbert. "Om center gravitatis uti ot skepp, ock om des fördelaktigare ställe, i anseende til skeppets fart" (On the Center of Gravity of a Ship, and Its Most Advantageous Place in Regard to Ship's Speed). *KVAH* (1742), pp. 81–92.

Simpson, Thomas. *Mathematical Dissertations on a Variety of Physical and Analytical Subjects*. London: T. Woodward, 1743.

Steel, David. *The Elements and Practice of Naval Architecture*. London: P. Steel Navigation Warehouse, 1805. Facsimile, London: Sim Comfort Associates, 1977.

Steel, David. *The Shipwright's Vade-Mecum*. London: P. Steel Navigation Warehouse, 1805. (Note: a vade mecum, literally "comes with me," is a handbook.)

Stevin, Simon. *Les Oeuvres mathématiques de Simon Stevin, vol. 4, L'Art pondénaire, ou la statique* (The Mathematical Works of Simon Stevin, vol. 4, The Art of Weighing or Statics), edited by Albert Girard. Leyden: Bonaventure et A. Elsevier, 1634.

Stevin, Simon. *The Principal Works of Simon Stevin*, edited by Ernst Crone, Eduard Jan Dijksterhuis, et al. translated by C. Dikshoorn, 5 vols. Amsterdam: C. V. Swets & Zeitlinger, 1955–1966.

Stibolt, Ernst Vilhelm. *Afhandling om skibes kiølbækkelighed, som viser aarsagera dertil og midlerne derimod, saa vidt som disse ere muelige at anbringe udi gode seylbare krigsskibe, af hvis skabninger man kan beregne, hvorvidt at et Skib er underkat at kiølbrydes meere end et andet: tilkiendt det Kongelige Videnskabernes Selskabs præmie i aaret 1776* (Treatise on Keelbreaking of Ships, Showing the Cause of It and the Means to Prevent It, as Far as It Is Possible to Prevent it in Good Sailing Warships, of Whose Bodies It Is Possible to Calculate Whether or Not a Ship Is Likely to Break Its Keel More Than Another: Awarded the Royal Danish Scientific Society's Prize in the Year 1776). Copenhagen: Stein, 1784.

Sutherland, William. *The Ship-builder's Assistant: Or Some Essays Towards Compleating the Art of Marine Architecture*. London: A. Bell & R. Smith, 1711.

Sutherland, William. *Britain's Glory: Or, Shipbuilding Unvail'd, Being a General Director, for Building and Compleating the Said Machines*, 2 vols. London: Norris, 1717.

Thévenard, Antoine-Jean Marie, count of. "Expériences sur la résistance des fluides" (Experiments on Fluid Resistance). *Mémoires relatifs à la marine*, 4 (1800).

Thévenard, Antoine-Jean Marie, count of. *Mémoires relatifs à la marine* (Memoirs Relative to the Navy). Paris: Laurens, 1800.

Varignon, Pierre. "Jaugeage d'un navire ellipsoïde" (Admeasurement of an Elliptical Ship). *HMAS* (1721), pp. 41–55.

Vauban, Sébastien Le Prestre de. Letter to François-Michel Le Tellier, marquis of Louvois, in a camp before Mannheim (14 November 1688). Printed in *Bulletin historique et philologique* (Historical and Philological Bulletin) (1888), pp. 238–240.

Vial du Clairbois, Honoré-Sébastien. *Essai géométrique et pratique sur l'architecture navale, à l'usage des gens de mer* (Geometrical and Practical Essay on Naval Architecture, for the Use of Seamen). Brest: Malassis, 1776.

Vial du Clairbois, Honoré-Sébastien. *Traité élémentaire de la construction des vaisseaux, à l'usage des élèves de la marine* (Elementary Treatise on the Construction of Vessels, for the Use of Navy Students). Paris: Clousier, 1782.

Vial du Clairbois, Honoré-Sébastien, ed. *Encyclopédie méthodique: Marine*. Paris: Panckouke, 1783–1787. Facsimile, Nice: Éditions Omega, 1987. 3 vols.

Voltaire (François Marie Arouet). *Lettres philosophiques* (Philosophical letters). Amsterdam: Lucas, 1734.

Voltaire (François Marie Arouet). *Alzire ou les américains* (Alzire, or the Americans). Paris: Claude Bauche, 1736.

Wallis, John. *Cono-cuneus or the Shipwright's Circular Wedge*. London: Playford, 1684. Appended to his *A Treatise of Algebra, Both Historical and Practical*. London: Playford, 1685.

Wallis, John. "A Discourse Concerning the Measure of the Air's Resistance to Bodies Moved in It." *PTRS* (1688), pp. 269–280.

Witsen, Nicolaes. *Aeloude en hedendaegsche scheeps-bouw en bestier* (Ancient and Modern Shipbuilding and Handling), Amsterdam: Casparus Commelijn & Broer en Jan Appelaer, 1671, Facsimile, Amsterdam: Canaletto-Alphen aan den Rijn, 1979. Reprinted with commentary in Hoving, Nicolaes Witsens *scheeps-bouw-konst open gestelt* Franeker [Netherlands], Van Wijnen (1994).

Yk, Cornelis van: *De Nederlandsche scheeps-bouw-konst open gestelt* (Dutch Shipbuilding Opened Up). Amsterdam: Ian ten Hoorn, 1697.

Zwijndregt, Pieter Pauluszoon van. *De groot Neederlandsche scheepsbouw op een proportionale reegel voorgesteld* (Presentation of Proportional Rules of the Great Netherlands Shipbuilding). Amsterdam: Nederlands Scheepvaartmuseum, 1757.

Secondary Sources

Abell, Westcott. *The Shipwright's Trade*. Cambridge: Cambridge University Press, 1948; Jamaica, NY: Caravan Book Service, 1962.

Acerra, Martine. "Les Constructeurs de la marine (XVII^e–XVIII^e siècle)" (The Constructors of the Navy [17th–18th Century]). *Revue historique* (1985), No. 343 pp. 283–304.

Acerra, Martine. *Rochefort et la construction navale française, 1661–1815* (Rochefort and French Naval Construction, 1661–1815), 4 vols. Paris: Librairie de l'Inde, 1993.

Acerra, Martine. "Du Maître de hache à l'ingénieur" (From Master of the Hatchet to Engineer). In her *L'Invention du vaisseau de ligne, 1450–1700* (The Invention of the Ship of the Line, 1450–1700), pp. 39–45. Paris: Kronos/SPM, 1997.

Acerra, Martine, and José-Patricio Merino Navarro. "Jean-François Gautier: Vie et influence d'un ingénieur marginal" (Jean-François Gautier: Life and Influence of a Marginal Engineer). *Neptunia* (1985), vol. 43 pp. 6–12.

Aiton, Eric John. *The Vortex Theory of Planetary Motions*. London: MacDonald, 1972.

Albion, Robert G. *Forests and Sea Power: The Timber Problem of the Royal Navy, 1652–1862*. Cambridge, MA: Harvard University Press, 1926. Reprinted Annapolis, MD: Naval Institute Press, 1999.

Alder, Ken. *Engineering the Revolution: Arms and Enlightenment in France, 1763–1815*. Princeton, NJ: Princeton University Press, 1997.

Alertz, Ulrich. "The Naval Architecture and Oar Systems of Medieval and Later Galleys." In *The Age of the Galley: Mediterranean Oared Vessels Since Pre-classical Times*, edited by Robert Gardiner. pp. 142–162. London: Conway Maritime Press, 1995.

Allard, Michel. *Henri-Louis Duhamel du Monceau et le Ministère de la Marine* (Henri-Louis Duhamel du Monceau and the Ministry of the Navy). Montreal: Leméac, 1968.

Anthiaume, Albert. "Pierre Bouguer (1698–1758)." In *Compte rendu de la 43^{me} session de l'Association Française pour l'Avancement des Sciences* (Report of the 43rd Session of the French Association for the Advancement of Science), Le Havre 1914 pp. 138–142.

Anthiaume, Albert. *Le Navire, sa construction en France et principalement chez les normands* (The Ship, Its Construction in France and Principally Among the Normans). Paris: Dumont, 1922; Marseille: Laffitte Reprints, 1980.

Appel, John Wilton. *Francisco José de Caldas: A Scientist at Work in Nueva Granada*. Philadelphia: American Philosophical Society, 1994.

Arrington, Elaine. "The Solid of Least Resistance: An Example from Newton's *Principia*," Unpublished manuscript, Oxford University (September 1997).

Arroyo, Ricardo. "Las enseñanzas de nautical en el siglo XVIII" (Nautical Education in the 18th Century). *Revista de historia naval* (Review of Naval History) (1994), No. 46 pp. 7–30.

Artiñano y de Galdácano, Gervasio de. *La arquitectura naval española (en madera), bosquejo de sus condiciones y rasgos de su evolución* (Spanish Naval Architecture (in Wood), a Sketch of Its Conditions and Characteristics of Its Evolution). Madrid and Barcelona: Oliva de Vilanova, 1920.

Artz, Frederick. *The Development of Technical Education in France 1500–1850*. Cambridge, MA: MIT Press, 1966.

Attoma-Pepe, François. “Un Aperçu du franc-bord des navires au Moyen-Age” (A Look at the Freeboard of Ships in the Middle Ages). *Bulletin technique du Bureau Veritas* (Technical Bulletin of Bureau Veritas) (January 1976), pp. 10–14.

Aulanier, Christiane. *Histoire du Palais et du Musée du Louvre* (History of the Palace and Museum of the Louvre). Paris: Éditions des Musées Nationaux, 1947–1971. (11 vols.)

Ausseau, J. P. “Un Essai de construction préfabriqué au XVII^e siècle” (A Trial of Prefabricated Construction in the 17th Century). *Neptunia* (1971), vol. 26 pp. 31–40.

Bagneux, Jean de. *Un Basque illustre: Renau d'Elissagaray, 1652–1719* (An Illustrious Basque: Renau d'Elissagaray, 1652–1719). Bayonne: Imprimerie de Courrier, 1932.

Baker, George Stephen. “Development of Hull Form of Merchant Vessels.” *TNECIES* (1938), vol. 54 pp. 33–66.

Baldwin, Martha. “Pious Ambition: Natural Philosophy and the Jesuit Quest for the Patronage of Printed Books in the Seventeenth Century.” In *Jesuit Science and the Republic of Letters*, edited by Mordechai Feingold, pp. 299–325. Cambridge, MA: MIT Press, 2003.

Bamford, Paul. *Forests and French Sea Power, 1660–1789*. Toronto: University of Toronto Press, 1956.

Bamford, Paul. *Fighting Ships and Prisons: The Mediterranean Galleys of France in the Age of Louis XIV*. Minneapolis: University of Minnesota Press, 1973.

Barber, Giles. “Who Were the Booksellers of the Enlightenment?” In *Buch und Buchhandel in Europa im achtzehnten Jahrhundert* (Books and the Book Trade in Europe in the Eighteenth Century), edited by Giles Barber and Bernard Fabian, pp. 211–224. Hamburg: Hauswedell, 1981.

Barker, Richard. Web site, <http://home.clara.net/rabarker>. Accessed December 2003.

Barker, Richard. “Fragments from the Pepysian Library.” *Revista da Universidade de Coimbra* (University of Coimbra Review), 32 (1986), pp. 161–178. Also on Barker Web site.

Barker, Richard. “‘Many May Peruse Us’: Ribbands, Moulds and Models in the Dockyards.” *Revista da Universidade de Coimbra* (University of Coimbra Review), 34 (1988), pp. 539–559. Also on Barker Web site.

Barker, Richard. “A Manuscript on Shipbuilding, circa 1620, Copied by Newton.” *Mariner's Mirror* (1994), vol. 80 pp. 16–29.

Barker, Richard. “English Shipbuilding in the Sixteenth Century: Evidence for the Processes of Conception and Construction.” In *Concevoir et construire les navires: De la Trière au picoteux* (Design and Build Ships: From Triremes to Fishing Boats), special edition of *Technologies/idéologies/pratiques: Revue d'anthropologie des connaissances* (Technologies/Ideologies/Practice: Revue of the Anthropology of Knowledge), edited by Eric Rieth, pp. 109–126. Aix-en-Provence: Erès, 1998.

Barker, Richard. "Ragusan Shipbuilding in the Mid-sixteenth Century: Some Evidence for Tonnage Measurement." Max Planck Institute of Shipbuilding Practice and Ship Design Methods Web site, <http://www.mpiwg-berlin.mpg.de/SHIP/main.html>. Accessed March 2002.

Barker, Richard. "Whole-Moulding: A Preliminary Study of Early English and Other Sources." In *Shipbuilding Practice and Ship Design Methods from the Renaissance to the 18th Century*, edited by Horst Nowacki and Matteo Valleriani, pp. 33–66. Preprint 245. Berlin: Max Planck Institute for the History of Science, 2003.

Beauchesne, Geneviève. *Historique de la construction navale à Lorient de 1666 à 1770* (History of Naval Construction at Lorient from 1666 to 1770). Vincennes: Service Historique de la Marine, 1980.

Bellamy, Martin. "English Master Shipwrights to the Danish Crown 1570–1690." *Mariner's Mirror* (1998), vol. 84 pp. 215–218.

Bellamy, Martin. "David Balfour: Early Modern Danish Ship Design." *Mariner's Mirror* (2006), vol. 92 pp. 5–22.

Bertin, Émile. "Notes on Waves and Rolling: Historical Introduction. Essay on Daniel Bernoulli." *Naval Science* (1873), pp. 344–351.

Birch, Thomas. *The History of the Royal Society of London for Improving of Natural Knowledge from Its First Rise*, 4 vols. London: Millar, 1756–1757. Reprinted New York: Johnson Reprint, 1968.

Bjerg, Hans Christian, and John Erichsen. *Danske orlogsskibe 1690–1860* (Danish Navy Ships 1690–1860). Copenhagen: Lademann, 1980.

Blanchard, Anne. *Les Ingénieurs du "roy" de Louis XIV à Louis XVI: Étude du Corps des Fortifications* (The "king's" Engineers from Louis XIV to Louis XVI: Study of the Corps of Fortifications). Montpellier: Déhan, 1979.

Blanco Núñez, José Maria. *La armada española en la primera mitad del siglo XVIII* (The Spanish Navy in the First Half of the 18th Century). Madrid: Izar Construcciones, 2001.

Bluche, François, ed. *Dictionnaire du grand siècle* (Dictionary of the Great Century). Paris: Fayard, 1990.

Blussé, Leonard, and Femme Gaastra, eds. *Companies and Trade*. Leiden: Leiden University Press, 1981.

Booker, Peter Jeffrey. "Gaspard Monge (1756–1818) and His Effect on Engineering Drawing and Technical Education." *Transactions of the Newcomen Society* (1961), vol. 34 pp. 15–36.

Booker, Peter Jeffrey. *A History of Engineering Drawing*. London: Chalto and Windus, 1963 / Northgate, 1979.

Boudriot, Jean. "Constructeurs et constructions navales à Rochefort aux XVII^e and XVIII^e siècles" (Naval constructors and Construction at Rochefort in the 17th and 18th Centuries). *Neptunia* (1985), vol. 43 pp. 14–25.

Boudriot, Jean. *Le Vaisseau de 74 canons: Traité pratique d'art naval* (The 74-Gun Vessel: Practical Treatise on Naval Art), 4 vols. Grenoble: Éditions des Quatre Seigneurs, 1973–1975. Translated by David H. Roberts as *The Seventy-four Gun Ship: A Practical Treatise on the Art of Naval Architecture*, 4 vols. Paris: Jean Boudriot Publications, 1986–1988.

Boudriot, Jean. *La Frégate dans la marine de France 1650–1850* (The Frigate in the French Navy 1650–1850). Paris: ANCRE, 1992. Translated by David H. Roberts as *History of the French Frigate 1650–1850*. Rotherfield, UK: Jean Boudriot Publications, 1993.

Boudriot, Jean. *Les Vaisseaux de 50 & 64 canons: Historique 1650–1780* (The 50 & 64-Gun Vessels: History 1650–1780). Paris: ANCRE, 1994.

Boudriot, Jean. *Les Vaisseaux de 74 à 120 canons: Historique 1650–1850* (The 74 to 120-Gun Vessels: History 1650–1850). Paris: ANCRE, 1995.

Boudriot, Jean. *Le Vaisseau trois-ponts du chevalier Tourville* (The Three-Decked Vessel of Sir Tourville). Paris: Jean Boudriot Publications, 1998.

Boudriot, Jean, and Hubert Berti. *Galiote à bombes La Salamandre, 1752*. Paris: ANCRE, 1982. Translated by David H. Roberts as *The Bomb Ketch Salamandre*. Paris: ANCRE, 1991.

Bourland, Richard D. “Maurepas and His Administration of the French Navy on the Eve of the War of the Austrian Succession (1737–1742).” Ph.D. dissertation, University of Notre Dame, 1978.

Bousquet-Bressolier, Catherine. “Charles-Antoine Jombert (1712–1784): Un Librairie entre science et arts” (Charles-Antoine Jombert (1712–1784): A Bookstore Between Science and the Arts). *Bulletin du bibliophile* (1997), vol. 2 pp. 299–333.

Brannigan, Augustine. *The Social Basis of Scientific Discoveries*. Cambridge: Cambridge University Press, 1981.

Brockliss, Laurence W. B. *French Higher Education in the Seventeenth and Eighteenth Centuries: A Cultural History*. Oxford: Clarendon Press, 1987.

Bronfenbrenner, Martha Ornstein. *The Rôle of Scientific Societies in the Seventeenth Century*. Chicago: University of Chicago Press, 1928; New York: Arno, 1975.

Brown, David K. *A Century of Naval Construction: The History of the Royal Corps of Naval Constructors, 1883–1983*. London: Conway Maritime Press, 1983.

Brown, David K. *Before the Ironclad: Development of Ship Design, Propulsion, and Armament in the Royal Navy 1815–1860*. London: Conway Maritime Press, 1990.

Brown, David K. “The Speed of Sailing Warships, 1793–1840: An Examination of the Evidence.” In *Les Empires en guerre et paix, 1793–1860* (Empires in War and Peace, 1793–1860), edited by Edward Freeman, pp. 155–193. Vincennes: Service Historique de la Marine, 1990.

Brown, David K. “How It All Began.” In *A Celebration of Naval Architecture 1791–1991*, special supplement to *The Naval Architect* (1991), pp. 5–7.

Brown, David K. "The Form and Speed of Sailing Warships." *Mariner's Mirror* (1998), vol. 84 pp. 298–307.

Brown, Harcourt. *Scientific Organizations in Seventeenth Century France (1620–1680)*. New York: Russell, 1934; 1967.

Brunel, Isambard. *The Life of Isambard Kingdom Brunel, Civil Engineer*. London: Longmans, Green, 1870. Reprinted Newton Abbot, UK: David & Charles Reprints, 1971.

Bruzeliuss, Lars. *Maritime History Virtual Archives*, <http://www.bruzeliuss.info/Nautica/Nautica.html>. (accessed Feb. 2003–Sept. 2004)

Burwash, Dorothy. *English Merchant Shipping 1460–1540*. Toronto: University of Toronto Press, 1947.

Calinger, Ronald. "Leonhard Euler: The First St. Petersburg Years (1727–1741)." *Historica Mathematica* 23 (1996), pp. 121–166.

Capel Sáez, Horacio, Joan Eugeni Sánchez, and Omar Moncada. *De Palas á Minerva: La formación científica y la estructura institucional de los ingenieros militares en el siglo XVIII* (From Pallas [Athena] to Minerva: The Scientific Formation and Institutional Structure of Military Engineers in the 18th Century). Madrid: CSIC; Barcelona: Serbal, 1988.

Cardwell, Donald Stephen Lowell. *The Organisation of Science in England*. London: Heinemann Educational, 1957; rev. ed., 1972.

Castro, Filipe Vieira de. *Ship Treatises Project*. Texas A&M Web site, <http://nautarch.tamu.edu/shiplab>. (accessed Dec. 2003)

Cerulus, Frans A. "Un Mathématicien mesure les navires" (A Mathematician Measures Ships). *Géomètre* (Surveyor), special edition of *Histoires de la mesure* (Stories of Measurement). pp. 34–37. Paris: Editions Publi-Topex, January 2001.

Cerulus, Frans A. "Comments on *Principes Hydrostatiques et Mécaniques*" (Principles of Hydrostatics and Mechanics). In *Die Werke von Daniel Bernoulli* (The Works of Daniel Bernoulli), vol. 8. Basel: Birkhäuser Verlag, 2004.

Cerulus, Frans A. "Comments on Daniel Bernoulli and Floating Bodies." In *Die Werke von Daniel Bernoulli* (The Works of Daniel Bernoulli), vol. 6. Basel: Birkhäuser Verlag, to appear.

Chaize, Thomas. "*La Construction navale au 17ème siècle: Étude du manuscrit de Paul Hoste, 'Architecture navale ou pratique de la construction des vaisseaux'*" (Naval Construction in the 17th Century: Study of the Manuscript of Paul Hoste, "Naval Architecture, or Practice of the Construction of Vessels"). Master's thesis, University of Poitiers, 1997.

Chaize, Thomas. "Étude graphique d'un manuscrit de construction navale: Étude du manuscrit de Paul Hoste, 'Architecture navale ou pratique de la construction des vaisseaux'" (Graphical Study of a Manuscript of Naval Construction: Study of the Manuscript of Paul Hoste, "Naval Architecture, or Practice of the Construction of vessels"). DEA dissertation, University of Poitiers, 1998.

Chandrasekhar, Subrahmanyan. *Newton's Principia for the Common Reader*. Oxford: Clarendon Press, 1995.

Chapelle, Howard. *The Search for Speed Under Sail, 1700–1855*. New York: Norton, 1967.

Charnock, John. *A History of Marine Architecture: Including an Enlarged and Progressive View of the Nautical Regulations and Naval History, Both Civil and Military, of All Nations, Especially of Great Britain; Derived Chiefly from Original Manuscripts . . . and Deduced from the Earliest Period to the Present Time*, 3 vols. London: R. Faulder 1800–1802.

Chartier, Roger, and Henri-Jean, Martin, eds. *Histoire de l'édition française, vol. 2, Le Livre triomphant 1660–1830* (History of the French Edition: The Book Triumphant, 1660–1830). Paris: Fayard, 1990.

Chesnais, René. “Les trois Bouguer et Le Croisic” (The Three Bouguers and Le Croisic). In *Pierre Bouguer, un savant breton au XVIII^e siècle* (Pierre Bouguer, a Breton Scholar in the 18th Century), edited by Institut Culturel de Bretagne (Cultural Institute of Brittany). pp. 9–31. Vannes: Institut Culturel de Bretagne, 2002.

Clowes, William Laird. *The Royal Navy: A History from the Earliest Times to the Present*, 7 vols. London: Sampson Low, 1897–1903. Reprinted as *The Royal Navy: A History from the Earliest Times to 1900*, 7 vols. London: Chatrham, 1996–1997.

Cohen, I. Bernard. “Isaac Newton, the Calculus of Variations, and the Design of Ships.” In *For Dirk Struik: Scientific, Historical, and Political Essays in Honour of Dirk J. Struik*, edited by Robert S. Cohen et al., pp. 169–187. Dordrecht: Reidel, 1974.

Cohen, I. Bernard. *Revolution in Science*. Cambridge, MA: Belknap Press of Harvard University Press, 1985.

Cohen, I. Bernard. *Science and the Founding Fathers*. New York: Norton, 1995.

Coles, Howard E. “The Contribution of British Defence Departments to Technical Education and Instruction from About 1700.” Ph.D. thesis, University of Manchester, 1984.

Concina, Ennio. “Humanism on the Sea.” In *Mediterranean Cities: Historical Perspectives*, edited by Irad Malkin and Robert Hohlfelder, pp. 159–165. Totowa, NJ: Frank Cass, 1988.

Concina, Ennio. *Navis: L'umanesimo su mare (1470–1740)* (Ships: Humanism on the Sea (1470–1740). Turin: Giulio Einaudi, 1990.

Cooper, Betty M. *Catalogue of the Scott Collection of Books, Manuscripts, Prints and Drawings*. London: Institution of Naval Architects, 1954.

Corvol, Andrée, ed. *Duhamel du Monceau 1700–2000: Un Européen du siècle des Lumières* (A European of the Enlightenment). Orléans: Académie d'Orléans, 2001.

Costabel, Pierre. “Une Leçon magistrale de Jean I Bernoulli” (A Magisterial Lesson from Jean I Bernoulli). In *Hommage à Gaston Bachelard: Études de philosophie et d'histoire des sciences* (Homage to Gaston Bachelard. Studies in the Philosophy and History of Science), edited by Georges Bouligand et al. Paris: Presses Universitaires de France, 1957.

Coste, Alain, and Pierre Crépel. "Comment imaginer un mathématicien du XVIII^e siècle?" (How to Imagine a Mathematician of the 18th Century?). *Matapli* (1994), vol. 38 pp. 43–49.

Crépel, Pierre. "Les Travaux d'un savant: Charles Romme 1745–1805" (The Works of a scholar: Charles Romme 1745–1805). In *Histoire et mémoire de l'Académie des Sciences* (History and Memoir of the Academy of Sciences), edited by Eric Brian and Christiane Demeulenaere-Douyère, pp. 291–310. Paris: Tec et Doc Lavoisier, 1996.

Cros, Bernard. "Verguin, un ingénieur bâtisseur, arpenteur des mers et de la terre" (Verguin, a Building Engineer, Surveyor of Oceans and the Earth). In *La Condamine et la mesure de la terre* (La Condamine and the Measure of the Earth). CD-ROM of the conference at the University of Social Sciences of Toulouse, edited by Jacques Le Pottier and Marie-Dominique Heusse. Toulouse, 21 May 2001.

Dainville, François de. "L'Enseignement scientifique dans les collèges des Jésuites" (Scientific Instruction in Jesuit Colleges). In *Enseignement et diffusion des sciences en France au XVIII^e siècle* (Instruction and Diffusion of Sciences in France in the 18th Century), edited by René Taton, pp. 27–65. Paris: Hermann, 1964.

Damianidis, Kostas A. "Methods Used to Control the Form of Vessels in the Greek Traditional Boatyards." In *Concevoir et construire les navires*, edited by Eric Rieth, pp. 217–244. Aix-en-Provence: Erès, 1998.

Darnton, Robert. *The Business of Enlightenment: A Publishing History of the Encyclopédie, 1775–1800*. Cambridge, MA: Belknap Press of Harvard University Press, 1979.

Dascal, Marcelo, and Cristina Marras. *The République des Lettres: A Republic of Quarrels?*, <http://www.tau.ac.il/humanities/philos/dascal/papers/republic1.html>. (accessed Dec. 2001)

Demerliac, Alain. *La Marine de Louis XIV: Nomenclature des vaisseaux du Roi-Soleil de 1661 à 1715* (Louis XIV's Navy: Nomenclature of the Vessels of the Sun King from 1661 to 1715). Nice: Éditions Omega, 1992.

Demerliac, Alain. *La Marine de Louis XV: Nomenclature des navires français de 1715 à 1774* (Louis XV's Navy: Nomenclature of French Ships from 1715 to 1774). Nice: Éditions Omega, 1995.

Demerliac, Alain. *La Marine de Louis XVI: Nomenclature des navires français de 1774 à 1792* (Louis XVI's Navy: Nomenclature of French Ships from 1774 to 1792). Nice: Éditions Omega, 1996.

Deng, Gang. *Maritime Sector, Institutions, and Sea Power of Premodern China*. Westport, CT: Greenwood Press, 1999.

Dessert, Daniel. *La Royale: Vaisseaux et marines du Roi Soleil* (The Royal Navy: Vessels and Sailors of the Sun King). Paris: Fayard, 1996.

Dessert, Daniel. *Tourville*. Paris: Fayard, 2002.

Dhombres, Jean. "Mettre la Géométrie en crédit: Bouguer et le métacentre" (Put Geometry in charge: Bouguer and the Metacenter). *Science et techniques en perspective* (Science and Technology in Perspective) (1999), Second series vol. 3 pp. 305–363.

Dhombres, Nicole, and Jean Dhombres. *Naissance d'un pouvoir: Sciences et savants en France, 1793–1824* (Birth of a Power: Science and Scholars in France, 1793–1824). Paris: Payot, 1989.

Dijksterhuis, Eduard Jan. *The Mechanization of the World Picture*, translated by C. Dikshoorn. Oxford: Clarendon Press, 1961.

Dingli, Laurent. *Colbert, marquis de Seignelay: Le Fils flamboyant* (Colbert, Marquis of Seignelay: The Flamboyant Son). Paris: Perrin, 1997.

Dirkzwager, Jan. "De voor geschiedenis van de opleiding tot scheepsbouwkundig ingenieur aan de Technische Universiteit Delft" (The History of Training the Shipbuilding Engineer until the Technical University of Delft). *Roering/Vereniging van Ingenieurs van Defensie* (Roering/Association of Defense Engineers) (1994), vol. 1 pp. 1–14.

Doneaud du Plan, Alfred. *Histoire de l'Académie de Marine* (History of the Academy of Navy). Paris: Berger-Levrault, 1878.

Dotson, John. "Treatises on Shipbuilding Before 1650." In *Cogs, Caravels, and Galleons: The Sailing Ship, 1000–1650*, edited by Robert Gardiner and Richard W. Unger, pp. 160–168. London: Conway Maritime Press, 1994.

Drake, Stillman. *Cause, Experiment, and Science: A Galilean Dialogue, Incorporating a New English Translation of Galileo's "Bodies That Stay atop Water, or Move in It."* Chicago: University of Chicago Press, 1981.

Drevet, Patrick. *Le Corps du monde* (The Body of the World). Paris: Seuil, 1997.

Driel, A. van. *Tonnage Measurement: Historical and Critical Essay*. The Hague: Government Printing Office, 1925.

Dugas, René. *A History of Mechanics*, translated by J. R. Maddox. Neuchâtel: Griffon, 1955; New York: Dover, 1988.

Duhem, Pierre-Marie-Maurice. *The Evolution of Mechanics*, translated by Michael Cole. Germantown, MD: Sijthoff & Noordhoff, 1903; 1980.

Duhem, Pierre-Marie-Maurice. *The Origins of Statics: The Sources of Physical Theory*, translated by Grant F. Leneaux et al. Dordrecht: Kluwer Academic, 1905; 1991.

Dunham, William. *Euler: The Master of Us All*. Washington, DC: Mathematical Association of America, 1999.

Dupont de Dinechin, Bruno. *Duhamel du Monceau: Un Savant exemplaire au siècle des Lumières* (Duhamel du Monceau: An Exemplary Scholar of the Enlightenment). Luxembourg: Connaissance et Mémoires Européennes, 1999.

Economic History Services Web site, *How Much Is That?*. <http://eh.net/hmit/ppowerbp>. (accessed June 2003)

Edwards, C. Henry. *Newton's Nose-Cone Problem*. University of Georgia, <http://www.math.uga.edu/~hedwards/articles/nosecone/nosecone.htm>. (accessed August 2000)

ENSIETA (École Nationale Supérieure des Ingénieurs des Études et Techniques d'Armement) Web site, <http://www.ensieta.fr>. (accessed December 2003)

ENSTA (École Nationale Supérieure de Techniques Avancées) Web site, <http://www.ensta.fr>. (accessed December 2003)

Erickson, Robert Finn. "The French Academy of Sciences Expedition to Spanish America, 1735–1744." Ph.D. dissertation, University of Illinois, Urbana, 1955.

Erlande-Brandenburg, Alain, and Catherine Vich. *Catalogue des plans des bâtiments à voiles conservés dans les archives de la marine* (Catalog of Plans of Sailing Ships Conserved in the Navy Archives). Vincennes: Service Historique de la Marine, 1996.

Erlo, J. d'. *Un Officier des armées de terre et de mer au temps de Louis XIV, Bernard Renau d'Elissagaray, chef d'escadre, lieutenant général des armées de terre, ingénieur militaire, membre de l'Académie des Sciences, grand croix de l'Ordre de Saint-Louis* (An Officer of the Armies of Sea and Land in the Time of Louis XIV, Renau d'Elissagaray, Fleet Commander, Lieutenant General of Land Armies, Military Engineer, Member of the Academy of Sciences, Great Cross of the Order of Saint Louis). Paris: Compagnie Française des Papiers-Monnaie, 1905.

Euler archive Web site, <http://www.eulerarchive.org>. (accessed December 2005)

Euler 2007 Web site, <http://www.euler2007.com>. (accessed June 2004)

Fauque, Danielle. "Tourbillons ou attractions: Les Physiciens du XVIII^e siècle entre un monde plein et un monde vide" (Vortices or Attractions: the Physicists of the 18th century Between a Full World and an Empty World). In *De la Nature: De la Physique classique au souci écologique* (On Nature: From Classical Physics to Ecological Awareness), edited by Pierre Colin. pp. 205–235. Paris: Beauchesne, 1992.

Fauque, Danielle. "Les Écoles d'hydrographie en Bretagne au XVIII^e siècle" (The Schools of Hydrography in Brittany in the 18th Century). *Mémoires de la Société d'Histoire et d'Archéologie de Bretagne* (Memoirs of the Society of History and Archeology of Brittany), (2000) vol. 78 pp. 369–400.

Fauque, Danielle. "Du Bon Usage de l'éloge: Cas de celui de Pierre Bouguer" (On the Correct Usage of the Eulogy: The Case of Pierre Bouguer). *Revue d'histoire des sciences*, (2001), vol. 54 pp. 351–382.

Feingold, Mordechai. "Jesuits: Savants." In *Jesuit Science and the Republic of Letters*, edited by Mordechai Feingold, pp. 3–39. Cambridge, MA: MIT Press, 2003.

Feldhay, Rivka. "The Cultural Field of Jesuit Science." In *The Jesuits: Cultures, Sciences, and the Arts 1540–1773*, edited by John W. O'Malley et al., pp. 107–127. Toronto: University of Toronto Press, 1999.

Fennebresque, Juste. *La Petite Venise, histoire d'une corporation nautique* (Little Venice, History of a Nautical Corporation). Paris: Picard et Fils, 1899.

Fernández González, Francisco. "Arqueología de la arquitectura naval" (Archaeology of Naval Architecture). In *Cátedra "Jorge Juan": Ciclo de conferencias curso 1994–1995* ("Jorge Juan" Chair, Conference Cycle Course 1994–1995), edited by Ramón de Vicente Vázquez, pp. 181–227. Ferrol: University of La Coruña, 1996.

Ferreiro, Larrie D. "Genius and Engineering: The Naval Constructors of France, Great Britain and the United States." *Naval Engineers Journal* (September 1998), vol. 110 pp. 99–132. Reprinted in *TRINA* (1999), vol. 141 pp. 160–191; and in *BATMA* (1999), vol. 98 pp. 281–335.

Ferreiro, Larrie D. "Down from the Mountain: The Birth of Naval Architecture in the Scientific Revolution, 1600–1800." Ph.D. thesis, University of London, 2004.

Filion, Maurice. *Maurepas, ministre de Louis XV* (Maurepas, Minister of Louis XV), Montreal: Éditions Leméac, 1967.

Fincham, John. *A History of Naval Architecture*. London: Whittaker, 1851; facsimile, London: Scholar Press, 1979.

Fitzmaurice, Edmund. *Life of Sir William Petty*. London: Murray, 1895.

Forsyth, Andrew Russell. "Newton's Problem of the Solid of Least Resistance." In *Isaac Newton 1642–1727*, edited by W. J. Greenstreet. London: G. Bell and Sons, 1927.

Fracard, Marie-Louise. "Un Disciple basque de Vauban, Renau d'Elissagaray et sa réforme fiscale manquée dans l'élection de Niort (1718–1723)" (A Basque Disciple of Vauban, Renau d'Elissagaray and His Failed Fiscal Reform in the Niort Election [1718–1723]). *Pyrénées*, no. 69 (January–March 1967).

Frängsmyr, Tore, ed. *Science in Sweden: The Royal Swedish Academy of Sciences, 1739–1989*. Canton, MA: Science History Publications, 1989.

Franklin, John. *Navy Board Ship Models, 1650–1750*. London: Conway Maritime Press, 1989.

Friedman, Norman. *U.S. Destroyers: An Illustrated Design History*. Annapolis, MD: Naval Institute Press, 1982.

Friedman, Norman. *Seapower as Strategy: Navies and National Interests*. Annapolis, MD: Naval Institute Press, 2001.

Friel, Ian. "The Carrack: The Advent of the Full-rigged Ship." In *Cogs, Caravels, and Galleons: The Sailing Ship, 1000–1650*, edited by Robert Gardiner and Richard W. Unger, pp. 80–91. London: Conway Maritime Press, 1994.

García-Frías, Juan. "Razón histórica del Examen marítimo" (Historical Reason for *Examen Marítimo*). *Revista general de marina* (General Journal of the Navy) (1973), vol. 184 pp. 643–653.

Gardiner, Robert. *The First Frigates: Nine-pounder and Twelve-pounder Frigates, 1748–1815*. London: Conway Maritime Press, 1992.

- Gardiner, Robert. *The Heavy Frigate: Eighteen-pounder Frigates, vol. 1, 1778–1800*. London: Conway Maritime Press, 1994.
- Gardiner, Robert. *Warships of the Napoleonic Era*. London: Chatham, 1999.
- Gardiner, Robert. *Frigates of the Napoleonic Wars*. London: Chatham, 2000.
- Gardiner, Robert, and Richard W. Unger, eds. *Cogs, Caravels, and Galleons: The Sailing Ship 1000–1650*. London: Conway Maritime Press, 1994.
- Gawronski, Jerzy, et al. *Hollandia Compendium: A Contribution to the History, Archeology, Classification and Lexicography of a 150 ft. Dutch East Indiaman (1740–1750)*. Amsterdam: Elsevier, 1992.
- Gilfillan, Seabury Colum. *Inventing the Ship: A Study of the Inventions Made in Her History Between Floating Log and Rotorship. A Self-contained but Companion Volume to the Author's "Sociology of Invention."* Chicago: Follett, 1935.
- Gille, Paul. "Les Écoles des constructeurs" (The Schools of the Constructors). In *Le Navire et l'économie maritime du XV^e au XVIII^e siècles* (The Ship and the Maritime Economy from the 15th Through the 18th Centuries), edited by Michel Mollat, pp. 161–176. Paris: SEVPEN, 1957.
- Gille, Paul. "Jauge et tonnage des navires" (Admeasurement and Tonnage of Ships). In *Le Navire et l'économie maritime du XV^e au XVIII^e siècles* (The Ship and the Maritime Economy from the 15th Through the 18th Centuries), edited by Michel Mollat, pp. 85–102. Paris: SEVPEN, 1957.
- Gillispie, Charles Coulston. *Science and Polity in France at the End of the Old Regime*. Princeton, NJ: Princeton University Press, 1980.
- Gillispie, Charles Coulston. *Science and Polity in France: The Revolutionary and Napoleonic Years*. Princeton, NJ: Princeton University Press, 2004.
- Gisserot, Paul. "Le Génie maritime et les arsenaux de la marine" (Maritime Engineering and the Navy Arsenals). In *Bi-centenaire du génie maritime 1765–1965* (Bicentennial of maritime engineering 1765–1965), edited by the Service de Propagande, Édition, Information (SPEI), pp. 1–88. La Chapelle-Montligeon: Imprimerie de Montligeon, 1965.
- Glete, Jan. *Navies and Nations: Warships, Navies and State Building in Europe and America 1500–1860*, 2 vols. Stockholm: Almqvist & Wiksell, 1993.
- Goldberg, Lawrence. "Intact Stability." In *Principles of Naval Architecture Second Revision*, 2nd ed., edited by Edward V. Lewis, pp. 63–142. Jersey City, NJ: SNAME, 1988.
- Greenberg, John L. *The Problem of the Earth's Shape from Newton to Clairaut: The Rise of Mathematical Science in Eighteenth-Century Paris and the Fall of "Normal" Science*. Cambridge: Cambridge University Press, 1995.
- Griffiths, Denis, Andrew Lambert, and Fred Walker. *Brunel's Ships*. London: Chatham, 1999.
- Grousset, André. "On a plongé sur la Lune" (We Dived on the Lune). *Sub Aqua* (January/February 1994), pp. 20–21.

Grousset, André. "Naufrage de la Lune" (Wreck of the Lune). *Capian* (September 2000), pp. 11–15.

Guicciardini, Niccolò. *Reading the Principia: The Debate on Newton's Mathematical Methods for Natural Philosophy from 1687 to 1736*. Cambridge: Cambridge University Press, 1999.

Guillén y Tato, Julio. *Los Tenientes de navío Jorge Juan y Santacilia y Antonio de Ulloa y de la Torre-Guiral, y la medición del meridiano* (The Naval Lieutenants Jorge Juan y Santacilia and Antonio de Ulloa y de la Torre-Guiral, and the Measure of the Meridian). Madrid: Galo Sáez, 1936. Reprinted Novelda (Alicante): Caja de Ahorros, 1973.

Haas, James M. "The Best Investment Ever Made: The Royal Dockyard Schools, Technical Education and the British Shipbuilding Industry, 1800–1914." *Mariner's Mirror* (1990), vol. 76 pp. 325–335.

Haas, James M. *A Management Odyssey: The Royal Dockyards, 1714–1914*. Lanham, MD: University Press of America, 1994.

Habicht, Walter. "Einleitung zu Band 20 der zweiten Serie" (Introduction to volume 20 of the Second Series). In Euler, *Opera Omnia*, 2nd ser., vol. 20 (1974).

Habicht, Walter. "Leonhard Eulers Schiffstheorie: Einleitung und Kommentar zu den Bänden 18 und 19 der zweiten Serie" (Leonhard Euler's Ship Theory: Introduction and Commentary on volumes 18 and 19 of the Second Series). In Euler, *Opera Omnia*, 2nd ser., vol. 21 (1978).

Hahn, Roger. "The Chair of Hydrodynamics in Paris, 1775–1791: A Creation of Turgot." In *Actes du dixième Congrès International d'Histoire des Sciences, 1962* (Proceedings of the 10th International Congress on the History of Science, 1962), edited by Henry Guerlac. Paris: Hermann, 1964.

Hahn, Roger. "L'Enseignement scientifique des Gardes de la Marine au XVIII^e siècle" (Scientific Instruction of the Marine Guards in the 18th Century). In *Enseignement et diffusion des sciences en France au XVIII^e siècle* (Instruction and Diffusion of Sciences in France in the 18th Century), edited by René Taton, pp. 547–558. Paris: Hermann, 1964.

Hahn, Roger. *L'Hydrodynamique au XVIII^e siècle: Aspects scientifiques et sociologiques* (Hydrodynamics in the 18th Century: Scientific and Sociological Aspects). University of Paris, Conférences du Palais de la Découverte, 7 November 1964, ser. D.100. Paris: University of Paris, 1965.

Hahn, Roger. *The Anatomy of a Scientific Institution: The Paris Academy of Sciences, 1666–1803*. Berkeley: University of California Press, 1971.

Hall, Alfred Rupert. *The Scientific Revolution 1500–1800: The Formation of the Modern Scientific Attitude*. New York: Longmans, 1954; 2nd ed., 1962.

Hall, Alfred Rupert. "Architectura Navalis." *Transactions of the Newcomen Society* (1979–1980), vol. 51 pp. 157–174.

Hall, Alfred Rupert. *The Revolution in Science 1500–1750*, 3rd ed. New York: Longmans, 1983.

Hambly, Maya. *Drawing Instruments, 1580–1980*. London: Sotheby's, 1988.

- Hankins, Thomas L. *Jean d'Alembert: Science and the Enlightenment*. Oxford: Clarendon Press, 1970.
- Harbron, John D. *Trafalgar and the Spanish Navy*. Annapolis, MD: Naval Institute Press, 1988.
- Harding, Richard. *Seapower and Naval Warfare, 1650–1830*. London: UCL Press, 1999.
- Harland, John H. *Seamanship in the Age of Sail*. London: Conway Maritime Press, 1984.
- Harley, Basil. "The Society of Arts' Model Ship Trials, 1758–1763." *Transactions of the Newcomen Society* (1991), vol. 63 pp. 53–71.
- Harris, Daniel G. *F. H. Chapman: The First Naval Architect and His Work*. London: Conway Maritime Press, 1989.
- Harris, Daniel G. "Francis Sheldon in Denmark 1686–1690." *Mariner's Mirror* (1997), vol. 83 pp. 293–302.
- Harris, John Raymond. "Copper and Shipping in the Eighteenth Century." *Economic History Review* (1966), vol. 29 pp. 550–569. Reprinted in Harris's *Essays in Industry and Technology in the eighteenth Century: England and France*, pp. 176–194. Brookfield, VT: Ashgate, 1992.
- Harris, Steven J. "Mapping Jesuit Science: The Role of Travel in the Geography of Knowledge." In *The Jesuits: Culture, Sciences and the Arts 1540–1773*, edited by John W. O'Malley et al., pp. 212–240. Toronto: University of Toronto Press, 1999.
- Havdrère, Philippe. *La Compagnie Française de, Indes au XVIII^e siècle (The French East Indies Company in the 18th century)*. Paris, Librairie de l'Inde, 1989.
- Henrat, Philippe. *Innovations techniques dans la marine, 1641–1817: Mémoires et projets reçus par le Département de la Marine (Marine G 86 à 119), inventaire analytique (Technical Innovations in the Navy, 1641–1817: Memoirs and Projects Received by the Navy Department ([ANF Fonds] Marine G 86 to 119), Analytic Inventory)*. Paris: Archives Nationales, 1990.
- Henwood, Philippe. "La Première Académie de Marine" (The First Academy of Navy). In *La Bretagne des savants et des ingénieurs 1750–1825 (Brittany of the Scholars and Engineers 1750–1825)*, edited by Jean Dhombres, vol. 1, pp. 36–40. Rennes: Éditions Ouest-France, 1991.
- Hepper, David J. *British Warship Losses in the Age of Sail 1650–1859*. Rotherfield, UK: Jean Boudriot Publications, 1994.
- Holmberg, Gustaf. "Svenska flottans fartygstyper och fartygsbyggen" (Swedish Fleet Ship Types and Shipbuilding). In *Svenskt skeppsbyggeri: En översikt av utvecklingen genom tiderna (Swedish Shipbuilding: An Overview of Development Through the Ages)*, edited by Gustaf Halldin, pp. 155–190. Malmö: Allhems Förlag, 1963.
- Holmes, George C. V. *Ancient and Modern Ships*. London: Wyman, 1906.
- Hoving, Albert. *Nicolaes Witsens scheeps-bouw-konst open gestelt (Nicolaes Witsen's System of Shipbuilding)* Franeker: Uitgeverij Van Wijnen, 1994.

Hoving, Albert, and Alan Lemmers. *In tekening gebracht: De achttiende-eeuwse scheepsbouwers en hun ontwerpmethoden* (Getting the Picture: Eighteenth-Century Shipbuilders and Their Design Methods). Amsterdam: De Bataafsche Leeuw, 2001.

Howarth, David. *The Men-of-War*. Alexandria, VA: Time-Life Books, 1978.

Iliffe, Robert. "'Aplatisseur du monde et de Cassini': Maupertuis, Precision Measurement and the Shape of the Earth in the 1730s." *History of Science* (1993), vol. 31 pp. 335–375.

Johns, Andrew. "An Account of the Society for the Improvement of Naval Architecture." *TINA* (1910), vol. 52 pp. 28–40.

Johnston, Stephen Andrew. "Making Mathematical Practice: Gentlemen, Practitioners and Artisans in Elizabethan England." Ph.D. dissertation, St. Johns College, Cambridge, May 1994.

Juan-García Aguado, José María de. *José Romero Fernández de Landa: Un ingeniero de marina en el siglo XVIII* (José Romero Fernández de Landa: A Naval Engineer in the 18th Century). La Coruña: Universidade da Coruña, 1998.

Juan-García Aguado, José María de. "Las características operativas de los navíos y fragatas del siglo XVIII" (Operating Characteristics of Ships and Frigates in the 18th century). *Revista de historia naval* (Review of Naval History) (1996), No. 55 pp. 65–80.

Kalmar Läns Museum Web site. <http://www.kalmarlansmuseum.se>. (accessed March 2002)

Keegan, John. *The Price of Admiralty: The Evolution of Naval Warfare*. New York: Viking, 1988.

Klein, Peter Wolfgang. "Origins of Trading Companies." In *Companies and Trade*, edited by Leonard Blussé and Femme Gaastra, pp. 17–28. Leiden: Leiden University Press, 1981.

Klemm, Friederich. *A History of Western Technology*, translated by Dorothea Waley Singer. New York: Scribner's, 1959.

Kline, Ronald. "Construing 'Technology' as 'Applied Science': Public Rhetoric of Scientists and Engineers in the United States, 1880–1945." *Isis* (1995), vol. 86 pp. 194–221.

Knight, Roger J. B. "The Introduction of Copper Sheathing into the Royal Navy." *Mariner's Mirror* (1973), vol. 63 pp. 299–309.

Kronick, David A. *A History of Scientific and Technical Periodicals: The Origins and Development of the Scientific and Technical Press, 1665–1790*, 2nd ed. Metuchen, NJ: Scarecrow Press, 1976.

Kronick, David A. *Comp. Scientific and Technical Periodicals of the Seventeenth and Eighteenth Centuries: A Guide*. Metuchen, NJ: Scarecrow Press, 1991.

Laeven, A. Hubert. *The "Acta Eruditorum" Under the Editorship of Otto Mencke (1644–1707): The History of an International Learned Journal Between 1682 and 1707*, translated by Lynne Richards. Amsterdam: APA-Holland University Press, 1990.

Lafuente García, Antonio, and Antonio Mazuecos. *Los caballeros de punto fijo: Ciencia, política y aventura en la expedición geodésica hispanofrancesa al virreinato del Perú en el siglo XVIII* (The

Gentlemen of the Fixed Point: Science, Politics and Adventure in the Hispanic/French Geodesic Expedition to the Viceroyalty of Peru in the 18th Century). Barcelona: Ediciones del Serbal; Madrid: CSIC, 1987.

Lafuente García, Antonio, and José Luis Peset. "Política científica y espionaje industrial en los viajes de Jorge Juan y Antonio de Ulloa (1748–1751)" (Scientific Politics and Espionage in the Voyages of Jorge Juan and Antonio de Ulloa [1748–1751]). *Mélanges de la Casa de Velázquez* (Assortments from the House of Velázquez) (1981), vol. 17 pp. 233–262.

Lafuente García, Antonio, and Manuel Sellés. *El observatorio de Cadíz (1753–1831)* (The Observatory of Cadiz [1753–1831]). Madrid: Ministerio de Defensa, 1988.

Lamandé, Pierre. "Théorie et pratique maritimes dans deux textes de Pierre Bouguer sur la mâture des vaisseaux" (Maritime Theory and Practice in two Texts of Pierre Bouguer on the Masting of Vessels). *Science et techniques en perspective* (Science and Technology in Perspective) (1999), second serie, vol. 3 pp. 365–396.

Lamb, Thomas, ed. *Ship Design and Construction*, 3rd ed. Jersey City, NJ: Society of Naval Architects and Marine Engineers (SNAME), 2003.

Lamontagne, Roland. *La Vie et l'oeuvre de Pierre Bouguer* (The Life and Work of Pierre Bouguer). Montreal: Presses de l'Université de Montréal, 1964.

Lamontagne, Roland. "Lettres de Bouguer à Euler" (Letters of Bouguer to Euler). *Revue d'histoire des sciences* (1966), vol. 19 pp. 225–246.

Lamontagne, Roland. *Ministère de la Marine: Maurepas et Pellerin d'après les sources manuscrites* (Ministry of the Navy: Maurepas and Pellerin from Manuscript sources). Montreal: Librairie de l'Université de Montreal, 1972.

Lamontagne, Roland. *Pierre Bouguer, 1698–1758: Un Blaise Pascal du XVIII^e siècle, suivi d'une correspondance* (Pierre Bouguer, 1698–1758: A Blaise Pascal of the 18th Century, Followed by Correspondence). Montreal: Roland Lamontagne, 1998.

Lane, Frederic Chapin. *Venetian Ships and Shipbuilders of the Renaissance*. Baltimore: Johns Hopkins University Press, 1934. Reprinted New York: Arno Press, 1979.

Lane, Frederic Chapin. "Venetian Maritime Law and Administration (1250–1350)." In *Studi in onore di Amintore Fanfani* (Essays in honor of Amintore Fanfani), vol. 3, pp. 21–50. Milan: Giuffrè, 1962.

Langen, Ulrik. "En fransk skibskonstruktør i Danmark—en beretning om emigranten Charles Louis Ducrest og skibet SVAR TIL ALT" (A French Ship Constructor in Denmark—an Account of the Emigrant Charles Louis Ducrest and the vessel SVAR TIL ALT). In *Handels- og Søfartsmuseet på Kronborg Årborg 2002* (Trade and Shipping Museum of Kronborg Yearbook. 2002) Kronborg: Danish Maritime Museum 2002.

Langins, Janis. *Conserving the Enlightenment: French Military Engineering from Vauban to the Revolution*. Cambridge, MA: MIT Press, 2004.

La Parra López, Emilio. *El regente Gabriel Ciscar: Ciencia y revolución en la España romántica* (The Regent Gabriel Ciscar: Science and Revolution in Romantic Spain). Madrid: Compañía Literaria, 1995.

La Roncière, Charles Bourel de. *Un Tricentenaire: Un Grand Ministre de la marine, Colbert* (A tricentennial: A Great Minister of the Navy, Colbert). Paris: Plon-Nourrit, 1919.

Laughton, L. G. Carr. "English and Spanish Tonnage in 1588." *Mariner's Mirror* (1958), vol. 44 pp. 151–154.

Lavery, Brian. *Building the Wooden Walls: The Design and Construction of the 74-Gun Ship Valiant*, London: Conway Maritime, 1991.

Lavery, Brian, and Simon Stephens. *Ship Models; Their Purpose and Development from 1650 to the Present*. London: Zwemmer, 1995.

Leidner, Allison. *The Lisbon Earthquake of 1755*. <http://pangea.stanford.edu>. (accessed April 2003)

Lemineur, Jean-Claude. *Les Vaisseaux du Roi Soleil* (The Vessels of the Sun King), Nice: Omega, 1996.

Lemmers, Alan. *Techniek op schaal: Modellen en het technologiebeleid van de marine 1725–1885* (Technology to Scale: Models and Technology Policy of the Navy, 1725–1885). Amsterdam: De Bataafsche Leeuw, 1996.

Lewis, Edward V., ed. *Principles of Naval Architecture*, 2nd ed. Jersey City, NJ: Society of Naval Architects and Marine Engineers (SNAME), 1988.

Llinares, Sylviane. *Marine, propulsion et technique: L'Évolution du système technologique du navire de guerre français au XVIII^e siècle* (Navy, Propulsion and Technology: The Evolution of the Technological System of French Warships in the 18th Century). Paris: Librairie de l'Inde, 1994.

Llinares, Sylviane. "La Flotte de la Compagnie Française des Indes au XVIII^e siècle: Une Normalisation inachevée" (The Fleet of the French East Indies Company in the 18th Century: An Unachieved Standardization). In *Les Flottes des Compagnies des Indes 1600–1857* (The fleets of the East Indies Companies 1600–1857), edited by Philippe Haudrère. Vincennes: Service Historique de la Marine, 1996.

López Sánchez, Juan Francisco, Manuel Valera Candel, and Carlos López Fernández. "La Academia de Guardias Marinas de Cartagena (1776–1824)" (The Academy of Navy Guards of Cartagena [1776–1824]). *Antilia* (1995), vol. 1 pp. 1–23.

Lutun, Bernard. "Une École pour les constructeurs des vaisseaux du roi de France (1740–1765): Le Projet de Duhamel du Monceau" (A School for the Vessel Constructors of the King of France: The Project of Duhamel du Monceau). *La Revue maritime* (trimester 3, 1994), pp. 107–134.

Lutun, Bernard. *La Marine de Colbert: Études d'organisation* (The Navy of Colbert: Studies in Organization). Paris: Economica, 2003.

Lyman, John. "Register Tonnage and Its Measurement." *American Neptune* (1947), vol. 7 pp. 223–234.

Lyon, David. *The Sailing Navy List: All the Ships of the Royal Navy—Built, Purchased, and Captured—1688–1860*. London: Conway Maritime Press, 1993.

Mach, Ernst. *The Science of Mechanics: A Critical and Historical Account of Its Development*, translated by Thomas J. McCormack. LaSalle, IL: Open Court Publishing, 1893; 6th ed., 1960.

Macleod, N. "The Shipwrights of the Royal Dockyards." *Mariner's Mirror* (1925), vol. 11 pp. 276–291.

Macleod, N. "Shipwright Officers of the Royal Dockyards." *Mariner's Mirror* (1925), vol. 11 pp. 355–369.

Maffioli, Cesare S. *Out of Galileo: The Science of Waters 1628–1718*. Rotterdam: Erasmus Publishing, 1994.

Maheu, Gilles. "Bibliographie de Pierre Bouguer (1698–1758) (Bibliography of Pierre Bouguer (1698–1758))." *Revue d'histoire des sciences* (1966), vol. 19 pp. 193–205.

Maheu, Gilles. "La Vie scientifique au milieu du XVIII^e siècle: Introduction à la publication des lettres de Bouguer à Euler" (Scientific Life in the middle of the 18th Century: Introduction to the Letters of Bouguer to Euler). *Revue d'histoire des sciences* (1966), vol. 19 pp. 206–223.

Manera Regueyra, Enrique, ed. *El buque en la armada española* (The Ship in the Spanish Navy). Madrid: Silex, 1981; 1999.

Marcil, Yasmine. "La Presse et le compte rendu de récits de voyage scientifique: Le Cas de la querelle entre Bouguer et La Condamine" (The Press and the Report of Accounts of a Scientific Voyage: The Case of the Quarrel Between Bouguer and La Condamine). *Science et techniques en perspective* (Science and Technology in Perspective), (1999), pp. 285–304.

Marker, Gary. *Publishing, Printing and the Origins of Intellectual Life in Russia, 1700–1800*. Princeton, NJ: Princeton University Press, 1985.

Martin, A. Lynn. *The Jesuit Mind: The Mentality of an Elite in Early Modern France*. Ithaca, NY: Cornell University Press, 1988.

Mary Rose Trust Web site. <http://www.maryrose.org>. (accessed July 2000)

Marzari, Mario. "L'arte della progettazione e della costruzione navale a Trieste tra il XVIII e il XIX secolo" (The Art of Naval Design and Construction in Trieste from the 18th to the 19th Century). In *Nave di legno* (Wooden Ships), 2nd ed., edited by Mario Marzari, pp. 181–192. Trieste: LINT, 1998.

Mascart, Jean. *La Vie et les travaux du Chevalier Jean-Charles de Borda (1733–1799): Episodes de la vie scientifique au XVIII^e siècle* (The Life and Works of Sir Jean-Charles de Borda (1733–1799): Episodes of the Scientific Life of the 18th Century). Paris: Rey, Lyon, & Picard, 1919.

Maurepas, Arnaud de, and Antoine Boulant. *Les ministres et les ministères des Lumières* (The Ministers and Ministries of the Enlightenment). Paris: Christian Editions, 1996.

Max Planck Institute for the History of Science. *History of Shipbuilding and Ship-Design Practice and Theory*, <http://www.mpiwg-berlin.mpg.de/SHIP/main.html>. (accessed Jan 2004)

McClellan, James E. III. *Science Reorganized: Scientific Societies in the Eighteenth Century*. New York: Columbia University Press, 1985.

McConnell, Anita. "La Condamine's Scientific Journey Down the River Amazon, 1743–1744." *Annals of Science* (1991), vol. 48 pp. 1–19.

McGee, David. "From Craftsmanship to Draftsmanship: Naval Architecture and the Three Traditions of Early Modern Design." *Technology and Culture* (1999), vol. 40 pp. 209–236.

McGee, David. "Ships and Science: English Naval Architecture 1600–1714." M.A. thesis, University of Toronto, 1999.

McGowan, Alan. *Tiller and Whipstaff: The Development of the Sailing Ship 1400–1700*. Vol. 3 in the series *The Ship*, edited by Basil Greenhill. Greenwich, UK: National Maritime Museum, 1981.

McNeill, John Robert. *Atlantic Empires of France and Spain: Louisbourg and Havana, 1700–1763*. Chapel Hill: University of North Carolina Press, 1985.

Mémain, René. *La Marine de guerre sous Louis XIV: Le Matériel. Rochefort, arsenal modèle de Colbert* (The War Navy Under Louis XIV: Matériel. Rochefort, Colbert's Model Dockyard). Paris: Hachette, 1937.

Merino Navarro, José-Patricio. *La armada española en el siglo XVIII* (The Spanish Navy in the 18th Century). Madrid: Fundación Universitaria Española, 1981.

Merino Navarro, José-Patricio. "Les Techniciens de haut niveau dans les arsenaux espagnols, 1730–1830" (Technicians of High Standing in Spanish Arsenals, 1730–1830). In *Le genti del mare Mediterraneo* (The Men of the Mediterranean Sea), edited by Rosalba Ragosta, vol. 2 pp. 1077–1095. Naples: Lucio Pironti, 1981.

Merton, Robert K. *Science, Technology and Society in Seventeenth Century England*. New York: Fertig, 1970.

Merton, Robert K. *The Sociology of Science*, edited by Norman W. Storer. Chicago: University of Chicago Press, 1973.

Mettas, Jean. *Répertoire des expéditions négrières françaises au XVIII^e siècle* (Collection of French Slave Ship Expeditions of the 18th Century), edited by Serge Daget, 2 vols. Paris: Société Française d'Histoire d'Outre-mer, 1978–1984.

Mikhailov, Gleb. "The Origins of Hydraulics and Hydrodynamics in the Work of the Petersburg Academicians of the 18th Century." *Fluid Dynamics* (1999), vol. 34 pp. 787–800.

Montucla, Jean Étienne. *Histoire des mathématiques* (History of Mathematics), 4 vols. Paris: Agasse, 1799–1802. Facsimile, Paris: Blanchard, 1968.

Morales Hernández, José Luis. "Jorge Juan, en Londres" (Jorge Juan, in London). *Revista general de Marina* (General Review of the Navy), (1973), vol. 184 pp. 663–670.

Morgan, Betty Trebelle. *Histoire du Journal des sçavans, depuis 1665 jusqu'en 1701* (A History of the *Journal of Scholars*, from 1665 Until 1701). Paris: Presses Universitaires de Paris, 1929.

Morineau, Michel. *Jauge et méthodes de jauge anciennes et modernes* (Admeasurement and Methods of Admeasuring, Ancient and Modern). Paris: Armand Colin, 1966.

Murat, Inès. *Colbert*. Paris: Fayard, 1980. Translated by Robert F. Cook and Jeannie van Asselt as *Colbert*. Charlottesville: University Press of Virginia, 1984.

Navarro, Victor. "Tradition and Scientific Change in Early Modern Spain: The Role of the Jesuits." In *Jesuit Science and the Republic of Letters*, edited by Mordechai Feingold, pp. 331–386. Cambridge, MA: MIT Press, 2003.

Needham, Joseph. *Science and Civilisation in China*, vol. 3. Cambridge: Cambridge University Press, 1961.

Neuville, Didier. "Les Établissements scientifiques de l'ancienne marine" (The Scientific Establishments of the Old Navy). *Revue maritime* (Maritime Review), 56 (1878), pp. 695–706; 57 (1878), pp. 333–363, 535–551; 59 (1879), pp. 60–74; 73 (1882), pp. 448–464; 76 (1883), pp. 599–624.

Neuville, Didier. *État sommaire des Archives de la Marine antérieures a la Révolution* (Summary Description of the Navy Archives Before the Revolution). Paris: Baudoin, 1898.

Nielsen, Eric. *Major Danish Warships Built at the Holmen Shipyard 1692–1744*, <http://www.milhist.dk>. (accessed Sept. 2003)

Nolhac, Pierre de. *La Création de Versailles* (The Creation of Versailles). Paris: Conard, 1925.

Novi, Carlos. The Marqués de la Victoria and the Advancement of Naval Lexicography in Eighteenth-Century Spain. *Mariner's Mirror* (1997), vol. 83 pp. 136–149.

Nowacki, Horst. "Splines im Schiffbau" (Splines in Shipbuilding). In *Das Schiff aus dem Computer* (The Ship out of the Computer): *Proceedings of the 21st Duisburg Colloquium Ship and Ocean Technology*, pp. 27–53. Duisburg: Institute of Ship Technology, 2000.

Nowacki, Horst. "Archimedes and Ship Stability." In *Proceedings of the Euroconference on "Passenger Ship Design, Operation and Safety,"* edited by Apostolos Papanikolaou and Kostas Spyrou. Athens: NTU, 2001. Reprinted as preprint 198. Berlin: Max Planck Institute for the History of Science, 2002.

Nowacki, Horst, and Larrie Ferreiro. "Historical Roots of the Theory of Hydrostatic Stability of Ships." In *Proceedings of the 8th International Conference on the Stability of Ships and Ocean Vehicles*, edited by Luis Pérez Rojas, pp. 1–30. Madrid: ETSIN 2003. Reprinted as Preprint 237. Berlin: Max Planck Institute for the History of Science, 2003.

Nowacki, Horst, and Matteo Valleriani, eds. *Shipbuilding Practice and Ship Design Methods from the Renaissance to the 18th Century*. Preprint 245. Berlin: Max Planck Institute for the History of Science, 2003.

OECD (Organization for Economic Cooperation and Development). *Main Economic Indicators*. Paris: OECD, 2004.

Ohrelius, Bengt. *Vasa: The King's Ship*, translated by Maurice Michael. London: Cassell, 1962.

Oldenziel, Ruth. *Making Technology Masculine: Men, Women and Modern Machines in America, 1870–1945*. Amsterdam: Amsterdam University Press, 1999.

O'Malley, John W. *The First Jesuits*. Cambridge, MA: Harvard University Press, 1993.

Orlogsmuseet (Danish Naval Museum) Web site, <http://www.orlogsbasen.dk>.

Owen, William Selkirk. "Geometry of the Ship." In *Principles of Naval Architecture*, edited by Henry Rossell and Lawrence Chapman, pp. 1–57. New York: SNAME, 1947.

Owen, William Selkirk, and John Niedermair. "Geometry of the Ship." In *Principles of Naval Architecture*, rev. ed., edited by John P. Comstock, pp. 1–53. New York: SNAME, 1967.

Pando Villarroya, José Luis de. *Jorge Juan y Santacilia, marino* (Jorge Juan y Santicilia, Mariner). Madrid: Pando Ediciones, 1984.

Parent-Charon, Annie. "Quel Publique pour le livre maritime dans le Paris du XVIII^e siècle? Le Livre maritime chez Claude-Antoine Jombert" (Which Public for the Maritime Book in 18th-century Paris? The Maritime Book at the House of Claude-Antoine Jombert). In *Le livre maritime du siècle des Lumières (The maritime book in the Enlightenment)*, edited by Annie Parent-Charon, Therry Claerr and François Moureau. Paris, Presses de l'Université Paris-Sorbonne, 2005 pp. 85–98.

Parker, Geoffrey. *The Military Revolution: Military Innovation and the Rise of the West, 1500–1800*. Cambridge: Cambridge University Press, 1988; 2nd ed., 1996.

Parker, Geoffrey, ed. *The Thirty Years' War*, 2nd ed., rev. London: Routledge, 1997.

Passeron, Irène. "Une Séance à l'Académie au XVIII^e siècle" (A Session at the Academy in the 18th Century). In *Histoire et mémoire de l'Académie des Sciences* (History and Memoir of the Academy of Sciences), edited by Eric Brian and Christiane Demeulenaere-Douyère, pp. 339–350. Paris: Tec et Doc Lavoisier, 1996.

Penzo, Gilberto. *Navi Veneziane/Venetian Ships*. Trieste: LINT, 2000.

Pepper, John. "Harriot's Manuscript on Shipbuilding and Rigging (ca. 1608–1610)." In *Five Hundred Years of Nautical Science, 1400–1900: Proceedings of the Third International Reunion for the History of Nautical Science and Hydrography*, edited by Derek Howse, pp. 204–216. Greenwich, UK: National Maritime Museum, 1981.

Peter, Jean. *Le Port et l'arsenal de Toulon sous Louis XIV* (The Port and Arsenal of Toulon Under Louis XIV). Paris: Economica, 1995.

Peter, Jean. *Les Barbaresques sous Louis XIV: Le Duel entre Alger et la marine du roi (1681–1698)* (The Barbars Under Louis XIV: The Duel Between Algiers and the King's Navy [1681–1698]). Paris: Economica, 1997.

Peter, Jean. *Les Artilleurs de la marine sous Louis XIV* (The Navy Artillerists Under Louis XIV). Paris: Economica, 1995.

Peter, Jean. *Une Stratégie de la terreur sous Louis XIV, les galiotes à bombes* (A Strategy of Terror Under Louis XIV: The Mortar Ship), <http://www.stratisc.org>. (accessed May 2003)

Phillips, Carla Rahn. *Six Galleons for the King of Spain: Imperial Defense in the Early Seventeenth Century*. Baltimore: Johns Hopkins University Press, 1986.

Picciola, André. *Le Comte de Maurepas: Versailles et l'Europe à la fin de l'ancien régime* (The Count of Maurepas: Versailles and Europe at the End of the Old Regime). Paris: Perrin, 1999.

Picon, Antoine. *French Architects and Engineers in the Age of Enlightenment*, translated by Martin Thom. Cambridge: Cambridge University Press, 1998.

Pollard, Jules Ambroise, and Auguste Dudebout. *Architecture navale: Théorie du navire* (Naval Architecture: Ship Theory). Paris: Gauthier-Villars, 1890–1894. (4 vols)

Poirier, Lucien. "L'École du Génie Maritime" (The School of Maritime Engineering). In *Bi-centenaire du génie maritime 1765–1965* (Bicentennial of Maritime Engineering 1765–1965), edited by Service de Propagande, Édition, Information (SPEI), pp. 183–214. La Chapelle-Montligeon: Imprimerie de Montligeon, 1965.

Pritchard, James. "From Shipwright to Naval Constructor: The Professionalization of 18th-Century French Naval Shipbuilders." *Technology and Culture* (1987), vol. 28, pp. 1–25.

Pritchard, James. *Louis XV's Navy, 1748–1762: A Study of Organization and Administration*. Montreal: McGill-Queen's University Press, 1987.

Rasmussen, Frank Allan. "The Royal Danish-Norwegian Dockyard: Innovation, Espionage and Centre of technology." In *European Historiography of Technology: Proceedings from the TISC Conference in Roskilde*, edited by Dan Ch. Christensen, pp. 41–54. Odense: Odense University Press, 1993.

Redondi, Pietro. "Along the water: the genius and the theory. D'Alembert, Condorcet and Bossut and the Picardy Canal controversy", *History and Technology* 1985 vol.2, pp. 77–110; reprinted in *The Civil Engineering of Canals and Railways before 1850*, edited by Milce Chrimes, pp. 143–176. Aldershot: Ashgate, 1997.

Reinders, H. Reinder, and Paul Kees. *Carvel Construction Technique: Skeleton-First, Shell-First. Fifth International Symposium on Boat and Ship Archaeology, Amsterdam 1988*. Oxford: Oxbow Books, 1991.

Renn, Jürgen, and Matteo Valleriani. *Galileo and the Challenge of the Arsenale*, preprint 179. Berlin: Max Planck Institute for the History of Science, 2001.

Reuss, Jeremias D. *Repertorium Commentationum a Societatibus Litterariis Editarum, Secundum Disciplinarum Ordinem* (Index of Articles Published by Scholarly Societies, Arranged by Discipline), 16 vols. Göttingen: Henricum Dieterich, 1801–1821. Facsimile, New York: Burt Franklin, 1961.

Rieth, Eric. *Le Maître-gabarit, la tablette et le trebuchet: Essai sur la conception non-graphique des carènes du Moyen-Âge au XXe siècle* (The Master-Frame, the Rising Square and the Trebuchet: Essay on the Nongraphic Design of Hulls from the Middle Ages to the 20th Century). Paris: Comité des Travaux Historiques et Scientifiques, 1996.

Rieth, Eric. "Les Débuts de l'enseignement à l'École de Construction de Toulon: *Le Livre de construction des vaisseaux* (1683) de François Coulomb (1654–1717)" (The Beginnings of Instruction at the School of Construction in Toulon: *The Book of Construction of Vessels* [1683] by François Coulomb [1654–1717]). In *Nave di legno* (Wooden Ships), 2nd ed., edited by Mario Marzari, pp. 111–118. Trieste, LINT, 1998.

Rieth, Eric. "Le Cas de la France à la fin du XVIIe siècle: Une Même Méthode de conception des navires au Ponant et au Levant (The Case of France at the End of the 17th Century: The Same Method of Ship Design in the Ponant and Levant). In *Proceedings: International Symposium on Archaeology of Medieval and Modern Ships of Iberian-Atlantic Tradition*, edited by Francisco Alves, pp. 259–268. Lisbon: Instituto Português de Arqueologia, 2001.

Rieth, Eric, ed. *Concevoir et construire les navires: De la Trière au picoteux* (Design and Build ships: From Triremes to Fishing Boats). Special edition of *Technologies/idéologies/pratiques: Revue d'anthropologie des connaissances* (Technologies/Ideologies/Practice: Revue of the Anthropology of Knowledge). Aix-en-Provence: Erès, 1998.

RINA Web site. <http://www.rina.org.uk>.

Robbs, Andrew. "Presidential Address." *TIESIS* vol.97 (1954), pp. 1–16.

Robertson, Frederick Leslie. *The Evolution of Naval Armament*. London: Constable, 1921; London: Storey, 1968.

Rodger, Nicholas A. M. *The Wooden World: An Anatomy of the Georgian Navy*. London: Collins, 1986.

Rodger, Nicholas A. M. "Form and Function in European Navies, 1660–1815." In *In het kielzog: Maritiem-historische studies aangeboden aan Jaap R. Bruijn bij zijn vertrek als hoogleraar zeegechiedenis aan de Universiteit Leiden* (In his Wake: Maritime Historical Studies in Honor of Jaap R. Bruijn on His Departure from the Professorship of Maritime History at the University of Leiden), edited by Leo Akveld et al., pp. 85–97. Amsterdam: De Bataafsche Leeuw, 2003.

Rodger, Nicholas A. M. "Image and Reality in Eighteenth-Century Naval Tactics." *Mariner's Mirror* (2003) vol. 89, pp. 280–296.

Rodger, Nicholas A. M. "Navies and the Enlightenment." In *Science and the French and British Navies, 1700–1850*, edited by Pieter van der Merwe; pp. 5–23. London: National Maritime museum, 2003.

Rodger, Nicholas A. M. *The Command of the Ocean: A Naval History of Britain 1649–1815*. New York: Norton, 2005.

Roger, Jacques. *Buffon: A Life in Natural History*, translated by Sarah Lucille Bonnefoi, edited by L. Pearce Williams. Ithaca, NY: Cornell University Press, 1997.

Rouse, Hunter, and Simon Ince. *History of Hydraulics*. Ames: Iowa State University Press, 1957; New York: Dover, 1963.

Royal Society Web site. <http://www.royalsoc.ac.uk>. (accessed Dec. 2003)

Rubio Serrano, José Luis. "Métodos de arqueo en el siglo XVI" (Methods of Admeasurement in the 16th Century). *Revista de historia naval* (Review of Naval History) (1989), No. 24 pp. 29–61.

Rubio Serrano, José Luis. *Arquitectura de la naos y galeones de las flotas de Indias, 1492–1590* (Architecture of Ships and Galleons of the Indies Fleet). Málaga: Ediciones Seyer, 1991. (2 vols)

Saint-Venant, Adhémar Jean Claude Barré de. "Résistance des fluids: Considérations historiques, physiques et pratiques" (Resistance of Fluids: Historical, Physical and Practical Considerations). *MAS*, 44 (1888), 1–280.

Salisbury, William. Tonnage measurement series in *Mariner's Mirror* (1966–1968): "Early Tonnage Measurement in England" (1966), vol.52 pp. 41–51; "Rules for Ships Built for, and Hired by, the Navy" (1966), vol.52 pp. 173–179; "Early Tonnage Measurement in England, Part III, H.M. Customs and Statutory Rules" (1966), vol.52 pp. 329–339; "Early Tonnage Measurement in England, Part IV, Rules Used by Shipwrights and Merchants" (1967), vol.53 pp. 251–264; "Early Tonnage Measurement in England, Part V, Colliers, Deadweight and Displacement Tonnage" (1968), vol. 54 pp. 69–75.

Sánchez Carrión, José Maria, and José Angel Cerrolaza Asenjo. "Solución al enigma de los orígenes del Cuerpo de Ingenieros de Marina: Ingeniería naval versus ingenieros navales" (Solution to the Enigma of the Origins of the Navy Corps of Engineers: Naval Engineering versus Naval Engineers). *Ingeniería naval* (December 2004), pp. 57–70.

Schaffer, Simon. "Fish and Ships: Models in the Age of Reason." In *Models: The Third Dimension of Science*, edited by Soraya de Chadarevian and Nick Hopwood, pp. 71–108. Stanford, CA: Stanford University Press, 2004.

Serbos, Gaston. "L'École Royale des Ponts et Chaussées" (The Royal School of Bridges and Roadways). In *Enseignement et diffusion des sciences en France au XVIII^e siècle* (Instruction and Diffusion of Sciences in France in the 18th Century), edited by René Taton, pp. 339–363. Paris: Hermann, 1964.

Seerup, Jakob. *Søkadetakademiet i Oplysningsstiden* (Naval Cadets Academy and the Enlightenment). Copenhagen: Marinehistoriske Skrifter, 2001.

Shapin, Steven. *The Scientific Revolution*. Chicago: University of Chicago Press, 1996.

Simón Calero, Julián. *La génesis de la mecánica de los fluidos* (The Genesis of Fluid mechanics). Madrid: UNED, 1996.

Simón Calero, Julián. "La mecánica de los fluidos en Jorge Juan." *Asclepio* (2001), vol. 53 pp. 213–280.

Šišević, Ivo. "Računanje obujma broda u Dubrovniku XVI vijeka" (Calculating a Ship's Volume in Dubrovnik in the 16th Century). *Anali Historijskog Instituta u Dubrovniku* (Annals of the Historical Institute of Dubrovnik) (1952), vol. 1 pp. 151–170.

Smith, James Raymond. *From Plane to Spheroid: Determining the Figure of the Earth from 3000 B.C. to the 18th Century Lapland and Peruvian Survey Expeditions*. Rancho Cordova, CA: Landmark Enterprises, 1986.

Sobel, Dava. *Longitude*. New York: Walker, 1995.

Sobrón Iruretagoyena, Marcelino, and Francisco Vuelta Fernández. "Breve análisis de algunos modelos teóricos aplicados a la teoría del comportamiento del flotador por el científico Jorge Juan y otros" (Brief Analysis of Some Theoretical Models Applied to the Theory of Movement of Floating Bodies, by the Scientist Jorge Juan and Others). In *I Simposio de historia de las técnicas: La Construcción naval y navegación* (First Symposium on the History of Technology: Naval Construction and Navigation), edited by Juan Achútegui Rodríguez, pp. 209–217. Santander: Universidad de Cantabria, 1996.

Soler Pascual, Emilio. *Viajes de Jorge Juan y Santacilia: Ciencia y política en la España del siglo XVIII* (Voyages of Jorge Juan y Santacilia: Science and Politics in 18th-Century Spain). Barcelona: Ediciones B, 2002.

Steele, Brett. "Muskets and Pendulums: Benjamin Robins, Leonhard Euler, and the Ballistics Revolution." *Technology and Culture* (1994), vol. 35 pp. 348–382.

Stoot, William Fred. "Ideas and Personalities in the Development of Naval Architecture." *TINA* (1958), vol. 100 pp. 215–223.

Stoot, William Fred. "Some Aspects of Naval Architecture in the Eighteenth Century." *TINA* (1958), vol. 100 pp. 31–46; *BATMA* (1958), vol. 57 pp. 127–165.

Stroup, Alice. "Louis XIV as Patron of the Parisian Academy of Sciences." In *Sun King: The Ascendancy of French Culture During the Reign of Louis XIV*, edited by David Lee Rubin, pp. 221–240. Washington, DC: Folger Shakespeare Library, 1992.

Sturdy, David J. *Science and Social Status: The Members of the Académie des Sciences, 1666–1750*. Woodbridge, UK: Boydell Press, 1995.

Sutton, Jean. *Lords of the East: The East India Company and Its Ships*. London: Conway Maritime Press, 1981.

Svensson, Av Sam. "Skeppsbyggeriet" (Shipbuilding). In *Svenskt skeppsbyggeri: En översikt av utvecklingen genom tiderna* (Swedish Shipbuilding: An Overview of Development Through the Ages), edited by Gustaf Halldin, pp. 91–108. Malmö: Allhems Förlag, 1963.

Symcox, Geoffrey. *The Crisis of French Sea Power, 1688–1697: From the Guerre d'Escadre to the Guerre de Course*. The Hague: Martinus Nijhoff, 1974.

Taillemite, Étienne. "Jean-Charles de Borda, ingénieur et marin 1733–1799" (Jean-Charles de Borda, Engineer and Sailor 1733–1799). In *Le Chevalier de Borda: Un Officier savant du XVIII^e siècle*

1733–1799 (Chevalier de Borda, an Officer-Scholar of the 18th Century 1733–1799), edited by the Musée de Borda (Dax, France), pp. 11–14. Biarritz: SAI, 1999.

Taton, René. “L’École Royale du Génie de Mézières” (Royal School of Engineering at Mézières). In *Enseignement et diffusion des sciences en France au XVIII^e siècle* (Instruction and Diffusion of Sciences in France in the 18th Century), edited by René Taton, pp. 559–615. Paris: Hermann, 1964.

Taton, René. “Le Rôle et l’importance des correspondances scientifiques aux XVII^e et XVIII^e siècles” (The Role and Importance of Scientific Correspondence in the 17th and 18th Centuries). In *René Taton: Études d’histoire des sciences, recueillies pour son 85e anniversaire* (René Taton: Studies in the History of Science, Collected for His 85th Birthday), edited by Danielle Fauque et al. Turnhout, Belgium: Brepols, 2000.

Thirriot, Claude. “Pouvoir politique et recherche hydraulique en France aux XVII^e et XVIII^e siècles” (Political Power and Hydraulic Research in France in the 17th and 18th Centuries). In *Hydraulics and Hydraulic Research: A Historical Review*, edited by Günther Garbrecht, pp. 103–113. Rotterdam: Balkema, 1987.

Timmermann, Gerhard. *Die Suche nach der günstigsten Schiffsform* (The Search for the Most Favorable Ship Form), Gerhard Stalling Hamburg: Verlag, 1979.

Timoshenko, Stephen. *History of Strength of Materials: With a Brief Account of Theory of Elasticity and Theory of Structures*. New York: McGraw-Hill, 1953; New York: Dover, 1983.

Tokaty, Gregory A. *A History and Philosophy of Fluid Mechanics*. Henley-on-Thames, Foulis, 1971.

Truesdell, Clifford Ambrose III. “Rational Fluid Mechanics (1687–1765).” In *Leonhardi Euleri Opera Omnia* (Complete Works of Leonhard Euler), 2nd ser., vol. 12, pp. i–cxxv. Bern: Orrell Füssli Turici, 1954.

Truesdell, Clifford Ambrose III. “Editor’s Introduction.” In *Leonhardi Euleri Opera Omnia* (Complete Works of Leonhard Euler), 2nd ser., vol. 13, pp. i–lxxi. Bern: Orrell Füssli Turici, 1955.

Truesdell, Clifford Ambrose III. “Rational Fluid Mechanics (1765–1788).” In *Leonhardi Euleri Opera Omnia* (Complete Works of Leonhard Euler), 2nd ser., vol. 13, pp. lxxiii–cii. Bern: Orrell Füssli Turici, 1955.

Truesdell, Clifford Ambrose III. “The Rational Mechanics of Flexible or Elastic Bodies (1638–1788).” In *Leonhardi Euleri Opera Omnia* (Complete Works of Leonhard Euler), 2nd ser., vol. 11, part 2. Bern: Orrell Füssli Turici, 1960.

Truesdell, Clifford Ambrose III. *Essays in the History of Mechanics*. New York: Springer-Verlag, 1968.

Truesdell, Clifford Ambrose III. “Euler’s Contribution to the Theory of Ships and Mechanics.” *Centaurus* (1983), vol. 26 pp. 323–335.

Trystram, Florence. *Le Procès des étoiles* (The Trial of the Stars). Paris: Seghers, 1979. Reprint Paris: Payot, 1997.

Tunstall, Brian, and Nicholas Tracy, eds. *Naval Warfare in the Age of Sail: The Evolution of Fighting Tactics 1650–1815*. Annapolis, MD: Naval Institute Press, 1990.

Turcat, Jean-Noël. "La Tragique Histoire de la *Lune*" (The Tragic Story of the *Lune*). *Neptunia* (Winter 1999), pp. 19–24.

Turpin, François-Henri. *Histoire des illustres français sortis du ci-devant tiers-état* (History of Illustrious Frenchmen from the Above Third Estate). Paris: Maradan, 1792.

Tursini, Luigi. "Leonardo da Vinci and the Problem of the Navigation and Naval Design." *TINA* (1953), vol. 95 pp. 97–102.

UPM ETSIN (Universidad Politécnica de Madrid, Escuela Técnica Superior de Ingenieros Navales). In *II centenario de las enseñanzas de ingeniería naval* (2nd Centennial of Naval Engineering Instruction). Madrid: ETSIN, 1975.

Vasa Museum Web site. <http://www.vasamuseet.se>. (accessed July 2000)

Vergé-Franceschi, Michel. *La Marine française au XIII^e siècle: Guerres, administration, exploration* (The French Navy in the 18th Century: Wars, Administration, Exploration). Paris: SEDES, 1996.

Vergé-Franceschi, Michel. *Marine et éducation sous l'ancien régime* (Navy and Education in the Old Regime). Paris: Éditions CNRS, 1991.

Vergé-Franceschi, Michel. *Chronique maritime de la France d'ancien régime* (Maritime Chronicle of France During the Old Regime). Paris: SEDES, 1998.

Vérin, Hélène. "Un 'Document technographique': Le Devis. Marine royale et fortifications aux XVII^e et XVIII^e siècles" (A "Mechanical Design" Document: The Written Estimate. Royal Navy and Fortifications in the 17th and 18th Centuries). *Techniques et cultures* (Technology and Cultures) (1987), vol. 9 pp. 141–167.

Vérin, Hélène. "Spectacle ou experimentation: La Préfabrication des vaisseaux en 1679. (Spectacle or experimentation: the prefabrication of vessels in 1679)" *Revue de synthèse* (Review of Synthesis) (1987), vol. 108 pp. 199–223.

Vérin, Hélène. *La Gloire des ingénieurs: L'Intelligence technique du XVI^e au XVIII^e siècle* (The Glory of Engineers: Technical Intelligence from the 16th Through the 18th Century). Paris: Albin Michel, 1993.

Vérin, Hélène. "L'Esppreuve du vaisseau qui a esté faite à Toulon en sept heures" (The Trial of the Vessel That Was Built in Toulon in Seven Hours). *Gérer et comprendre, série des Annales des mines* (Manage and Understand, series of the *Annals of Mines*), no. 42 (February 1996), pp. 23–35.

Villiers, Patrick. *La marine de Louis XVI. vol. 1, Vaisseaux et frégates, de Choiseul à Sartine* (The Navy of Louis XVI. vol. 1, Vessels and Frigates, from Choiseul to Sartine). Grenoble: J. P. Debbane, 1985.

Villiers, Patrick. *Marine royale, corsaires et trafic dans l'Atlantique de Louis XIV à Louis XVI* (Royal Navy, Corsairs and Traffic in the Atlantic from Louis XIV to Louis XVI). Dunkerquo: Société Dunkerquoise d'Histoire et d'Archéologie, 1991.

Villiers, Patrick. "De la Lutte contre la maladie du safran à la direction de l'inspection générale de la construction navale, une alliance inattendue: Duhamel du Monceau et Maurepas"

(From the Fight Against the Saffron Sickness to the Direction of General Inspection of Naval Construction, an Unexpected Alliance: Duhamel du Monceau and Maurepas). In *Eighth Anglo-French Naval Historians Conference. The Rational and the Irrational: Science and the French and British Navies, 1700–1850*. Greenwich: National Maritime Museum, 2001.

Vincenti, Walter G. *What Engineers Know and How They Know It: Analytical Studies from Aeronautical History*. Baltimore: Johns Hopkins University Press, 1990.

Vischer, Daniel. "Daniel Bernoulli and Leonhard Euler: The Advent of Hydromechanics." In *Hydraulics and Hydraulic Research: A Historical Review*, edited by Günther Garbrecht, pp. 145–156. Rotterdam: Balkema, 1987.

Whitaker, Robert. *The Mapmaker's Wife: A True Tale of Love, Murder, and Survival in the Amazon*. New York: Basic Books, 2004.

Whiteside, Derek Thomas, ed. *The Mathematical Papers of Isaac Newton, vol. 6, 1684–1691*. Cambridge: Cambridge University Press, 1974.

Wikipedia Online Encyclopedia. <http://en.wikipedia.org>. (accessed Dec. 2003)

Wooley, Joseph. "On the Present State of the Mathematical Theory of Naval Architecture." *TINA* (1860), vol. 1 pp. 10–38.

Wright, Thomas. "Ship Hydrodynamics 1710–1880." Ph.D. thesis, University of Manchester, 1983.

Wright, Thomas. "Mark Beaufoy's Nautical and Hydraulic Experiments." *Mariner's Mirror* (1989), vol. 75 pp. 313–327.

Zagreb University. *Centuries of Natural Science in Croatia*, http://jagor.srce.hr/zuh/English/nv17_e.htm. (accessed Dec. 2000)

Zanelli, Guglielmo. "La scuola di 'naval architettura' nell'arsenale di Venezia" (The School of Naval Architecture in the Arsenal of Venice). In *Nave di legno* (Wooden Ships), edited by Mario Marzari, pp. 139–144. Trieste: LINT, 1997.

Ziggelaar, August. *Le Physicien Ignace Gaston Pardies S.J. (1636–1673)* (The Physicist Ignace Gaston Pardies S.J. (1636–1673). Odense: Odense University Press, 1971.

Zuckerman, Harriet. "The Sociology of Science." In *The Handbook of Sociology*, edited by Neil Smelser, pp. 511–574. Newbury Park, CA: Sage, 1988.

Index

- Academia de Ingenieros*. *See* Academy of Engineers Ferrol
- Académie de Marine*. *See* Academy of Navy Brest
- Academies and societies, 57–59, 61–62, 302
- Academy of Engineers Ferrol, 292
- Academy of Navy Brest, 58, 98, 160, 301, 309
- Academy of Science and Literature Berlin, 56, 58–59, 119, 147, 148, 149, 302
- Academy of Sciences and Letters Denmark, 59
- Academy of Sciences Paris
and admeasurement study (1722), 5, 103, 194, 203–205, 238
closure of, 174, 301–302
and the Geodesic Missions, 8–9, 58, 307
history of, 57–58, 63
in the Louvre, 58, 286
and proximity to the Little Navy School, 286
publications of, 54, 56, 58
and support of naval architecture and technology, 6, 121, 286, 288
ties with the Academy of Navy Brest, 58, 301
- Academy of Sciences Paris, Rouillé de Meslay Prize, 58, 104, 121
- Prize on masting (1727), 5–6, 103–108, 119, 214–217, 221, 266 (*see also* Masting of ships; *Point vélique*)
- Prizes on roll, pitch and lading (1755–1765), 253–255
- Academy of Sciences Saint Petersburg, 56, 59, 119, 145, 148, 219, 222, 251, 266, 269, 302
- Academy of Sciences Sweden, 59, 246, 302
- Admeasurement (volumetric tunnage), xix, 5, 43, 191–194. *See also* Academy of Sciences Paris, admeasurement study
- Admiralty coefficient of resistance, 184
- Anglo-French sailing trials (1832), 178–179
- Archimedes, 312
and hydrostatics and stability of floating bodies, ix, 105, 194, 195, 207–209, 214–215, 232
and virtual displacement/lever laws, 114–115, 214
- Aristotle, 103, 114–115, 195, 214, 261, 262, 298, 312
- Arsenal of Venice. *See* Venice, Arsenal of
- Atwood, George, 256–257, 302–303, 312
- Baker, Mathew, 43, 123–124, 127, 312
and *Fragments of Ancient English Shipwrighty* (1570), 41, 46–47, 193
- Beaufoy, Mark, 114, 167, 183, 302
- Bélibor, Bernard Forest de, 206, 280
- Benstrup, Knud, 199
- Bentam, Charles, 39, 41
- Berlin Academy of Science. *See* Academy of Science and Literature Berlin
- Bernoulli, Daniel, 312

- and *Hydrodynamica* (1738), 144–146
- and live forces, 117, 127, 145
- and roll and pitch theory, 250–251, 253–255
- Bernoulli, Jacob, 89, 91, 102, 118, 252, 312
- Bernoulli, Johann, xvii, 119, 132–134, 312
- and debate with Renau over the *derive* (1712–1714), 87, 88, 91, 92–94
- and *Essay d'une nouvelle Théorie de la Manoeuvre des Vaisseaux* (1714), 60, 93, 95–96, 98, 102, 103, 108
- and “Hydraulica” (1743), 144–146
- Bernoulli laws (equations), 102, 144–145
- Bignon, Jean-Paul, 5, 6, 10, 104, 203
- Bonjean, Antoine Nicolas François, vii–viii, 312
- Book publishing, 55–57, 61–62
- Borda, Jean Charles de, 313
 - as head of French naval constructors, 289–290
 - and hydrodynamics experiments, 150, 160–161, 163, 171, 176, 179–180, 244
 - and standardization of ship designs with Sané, 35, 179, 239, 287
- Bossut, Charles, 55, 62, 163, 254, 280
 - and hydrodynamics experiments, 163–168, 171, 176, 303, 313
- Bouguer, Jean (father of Pierre), 3–5, 309
- Bouguer, Pierre. *See also* *Traité du navire* (1746)
 - and the Academy of Sciences Paris, 5–6, 58, 203–204
 - and the Academy of Sciences Prize on masting (1727), 5–6, 51, 55, 103–108, 134, 221
 - biography of, 1–7, 309–310, 313
 - and bows of least resistance, 134–137
 - and use of calculus, 5, 98
 - as central figure in the history of naval architecture, x
 - death of, 309–310
 - and *De la Manoeuvre des Vaisseaux* (1757), 98–102, 252, 309
 - and Euler, comparison with, 135–138
 - and Euler, correspondence with, 309
 - and the Geodesic Mission to Peru, 10–18, 20, 22, 116, 135, 146, 307, 308
 - and maneuvering theory, 96–98
 - and the metacenter, 7–8, 227–232
 - and the quarrel with La Condamine, 307–308
 - and ratio of bow resistance, 137, 140, 173
 - and relationship with Maurepas, 6, 7, 28–29, 93, 97, 102, 104, 191, 307–308
 - and roll and pitch theory, 251–253
 - and stability theory (1727), 106, 215, 216
 - and stability theory (1732–1746), 227–237
 - and the trapezoidal method, 203–205, 228
 - on weight estimating, 206–207
 - wounded during Geodesic Mission to Peru, 16
- Bourdé de Villehuet, Jacques-Pierre, 60, 99–100, 108, 255, 313
- Bourne, William, 194, 200
- Bows of least resistance, 134–137, 163. *See also* Solid of least resistance
- Britain, naval constructors of. *See* Naval constructors of Britain
- Britain, survey of navy, 30–31
- British East India Company, 33, 191
- British warships, speed compared with French warships, 176–178
- Brunel, Isambard Kingdom, 183, 184, 302, 304–305
- Buffon, Georges-Louis Leclerc, count of, 284
- Bureaucratic control of ship design
 - by ship models, 38, 40, 42, 65, 66
 - by ship plans, 38, 42
 - by ship theory/naval architecture, x, 25, 279, 286–287, 303–304
- Burgues de Missiessy-Quières, Édouard Jacques, count of, 60, 255n155, 313
- Bushnell, Edmund, 197, 203
- Calculus, 5, 114
 - and the priority dispute between Newton and Leibniz, 132, 233, 237

- Calculus, differential
 in maneuvering theory, 98
 in sails as curved surfaces, 101–102
 in the solid of resistance, 129–131
- Calculus, integral
 in stability theory, 221–222
 numerical approximation by the method of trapezoids, 203–205, 228, 265
 numerical approximation by Simpson's Rule, 246–247, 257, 277
- Calculus, partial differential
 in a vector field, 146, 147
 in fluid continuity and dynamics equations, 149–150
- Camus, Charles Étienne Louis, 12, 104–105, 215–217, 280, 284, 313
- Cannon, naval, and effect on ship design, 34–35
- Carpenters, as ship constructors, xvii, 23, 287–288
- Cassini, Giovanni Domenico, 8–9, 13, 58, 126
- Castries, Charles Eugène Gabriel de La Croix, marquis of, 179, 287, 313
- Catamarans, of William Petty, 57, 126, 138, 197
- Center of gravity, calculation of, 242–243. *See also* Inclining experiment
- Center of oscillation, 98, 99, 117–118
- Center of rotation experiment, 99, 100, 101
- Chapman, Fredrik Henrik af, 59, 294, 314. *See also* *Tractat om Skepps-Byggeriet* (1775) and *Architectura Navalis Mercatoria* (1768), 49, 246, 277, 278
 as chief constructor of Swedish navy, 30, 246
 and the creation of the Fleets Constructor Corps, 295
 and model experiments, 153–158, 173, 176
 parabola method of, 158, 278
 relaxation method of, 154–158, 303
 and Simpson's rule, 246–247, 257, 277
 study abroad, 153–154, 246
- Charnock, John, and *A History of Marine Architecture* (1800), xii, 139–140
- Chauchot, 253
- China, and standardization of ships, 38
- Choiseul, Étienne-François, duke of, 29, 110, 143, 239, 243, 245, 286–287, 293, 314. *See also* 1765 Shipbuilding Ordinance
- Clairaut, Alexis-Claude, 12, 144, 146–149, 253, 263, 314
- Clairin-Deslauriers, François Guillame, 110, 242, 243, 284, 314
- Cod's head and mackerel's tail, 123–124
- Colbert, Jean Baptiste
 and the Academy of Sciences Paris, 57, 58, 63
 biography of, 62–63, 314
 and the Construction Conferences (1681), 74–79
 rebuilding the French navy, 28, 62–64, 280–281
 and Renau, 28, 51, 68–70, 81
 and the search for a theory of ships, 37, 65–68, 74, 75–80, 82, 120–121
 shipbuilding regulations of, 39, 48, 65, 66, 71, 79, 194, 286
 and standardization of ship designs, 35, 37–38, 49
 and the Versailles Grand Canal, 67–68, 75–78, 151
- Compagnie des Indes. *See* French East Indies Company
- Condorcet, Marie-Jean-Antoine-Nicholas Caritat, marquis of, 121, 164–167, 269n15, 308, 314
- Cono-cuneus, of John Wallis, 123, 126, 127, 136
 used as hull form for design of *Royal Katherine*, 138
- Construction Conferences (1681), 74–80
- Constructor, definition of, xvii
- Constructors. *See* Naval constructors
- Copper sheathing, 37
- Coriolis, Gustave Gaspard, 136, 145, 167

- Corps des Ingénieurs-Constructeurs de la Marine.*
See Naval constructors, France
- Corps des Ingénieurs des Ponts et Chaussées.* See Corps of Engineers of Bridges and Roadways
- Corps du Génie Maritime.* See Naval constructors, France
- Corps du Génie Militaire.* See Corps of Military Engineers, France
- Corps of Engineer-constructors of the Navy, France. See Naval constructors, France
- Corps of Engineers of Bridges and Roadways, France, 280
- Corps of Engineers, Spain, 245, 290
- Corps of Maritime Engineering, France, Special School of. See Little Navy School
- Corps of Maritime Engineering, France. See Naval constructors, France
- Corps of Military Engineers, France, 56, 81, 92, 160, 167, 279–280, 288
- Corps of Navy Engineers, Spain. See Naval constructors, Spain
- Coulomb, Charles Augustin de (scientist), 150, 182
- Coulomb, François (constructor 1600s), 75
- Coulomb, François (constructor 1700s), 217
- Coulomb, Laurent (constructor 1600s), 75, 77
- Coulomb, Pierre (constructor 1700s), 33
- Cuerpo de Ingenieros de Marina.* See Naval constructors, Spain
- Cuerpo de Ingenieros.* See Corps of Engineers, Spain
- Currency conversion. See money conversion
- D'Alembert, Jean-Louis Le Rond, 314
and hydrodynamic experiments 164–167
hydrodynamic theories of, 144, 146–148, 252–253
paradox of, 147
- Danish Academy of Sciences, 59
- Dassié, Charles, xiv, 48, 71
- De la Théorie de la manoeuvre des vaisseaux* (1689) by Renau, 46, 60, 62, 81–87
as first published work of naval architecture, 82
- Deadweight (cargo tonnage), calculation of, 199–205
- Deane, Anthony, 31, 41, 48, 68–69, 151, 314
and calculating displacement, 196–199, 248
- Denmark, naval officer-constructors of. See Naval constructors, Denmark
- Denmark, survey of navy, 30
- Dérive*
debate between Renau and Huygens (1691–1696), 88–91, 93
debate between Renau and Johann Bernoulli (1712–1714), 87, 88, 92–94
Pardies' analysis in *La Statique* (1673), 69–70
Renau's analysis in "Mémoire sur les constructions des vaisseaux" (1679), 71–73
Renau's analysis in *De la Théorie de la manoeuvre des vaisseaux* (1689), 81–87
- Descartes, René, 8, 69, 73–74, 115–117
- Descriptive geometry, 43
- Digges, Thomas, xiv, 47
- Displacement, calculations of, 196–202
due to gun ports, 35, 43
due to shallow Drogden Straits, 199
faulty ideas about, 195–196
reconciled with weights, 205–207
- Doctrine. See also Naval tactics
balance of power, 27
effect on ship design, 37–38
- Double tangent rule of sail, 98, 99, 100–101
- Du Buat, Pierre-Louis-Georges, 60, 121, 164, 168–171, 174, 176, 181, 182, 280, 315
- Ducrest, Charles-Louis, marquis of 60, 182
- Duhamel du Monceau, Henri Louis, 315. See also *Éléments de l'Architecture Navale* (1752); Little Navy School
as chief constructor of French navy, 284
and his relationship with Bouguer, 266, 270, 309
and his relationship with Maurepas, 29, 269, 283–284

- and the 1765 Shipbuilding Ordinance, 386–387
- Duquesne, Abraham, 66, 74–80, 315
- East Indies companies, survey of, 32–33
- École de Paris*. *See* Little Navy School
- École des Élève Ingénieurs-Constructeurs de la Marine*. *See* Little Navy School
- École du Louvre*. *See* Little Navy School
- École Polytechnique*, 289
- Éléments de l'Architecture Navale* (1752) by Duhamel du Monceau, xi, 49, 57, 60, 61, 62, 100, 110, 140, 238, 245, 248, 286
- description of, 269–272
- Ellipse theory of ships, by Renau, 46, 71–74, 78, 79, 80, 88, 133
- Elvius, Pehr, 99, 109, 315
- Encyclopédie* by Diderot and D'Alembert (1751–1772), 55, 61
- Encyclopédie méthodique Marine* (1783–1787), 61, 181, 182–183, 275
- Engineer-constructors of the Navy, France. *See* Naval constructors, France
- Engineer-constructors of the Navy, France, School of. *See* Little Navy School
- Engineering
- definition of, xiv–xv, 279
- as a tool for optimization, 301, 304
- Ensenada, Zenón de Somodevilla y Bengoechea, marquis of, 29, 272, 274
- Espionage, as a means of technology transfer, 64, 80, 139, 176, 272, 274, 291, 294
- Euler, Johann Albrecht, 254–255
- Euler, Leonhard, 53, 56, 59, 177. *See also* *Scientia navalis* (1749)
- and the Academy of Sciences Prize on masting (1727), 104–105
- biography of, 119–120, 315
- and Bouguer, comparison with, 135–138
- and Bouguer, correspondence with, 309
- and bows of least resistance, 135–137
- hydrodynamic theories of, 144, 149–150, 182
- and maneuvering theory, 97–98
- and roll and pitch theory, 250, 252, 254
- and stability theory (1727), 105, 214–215
- and stability theory (1735–1749), 219, 222–227, 233–237
- Europe, survey of navies, 26–32
- Examen Marítimo* (1771) by Juan y Santacilia, xi, 19, 23, 60, 98, 102, 180–181, 244–245, 292
- description of, 272–275
- Experimentation, assessment of hull forms
- in Britain (1670–1750s), 139, 151–153
- by Chapman (1770s–1797), 153–158, 173, 176
- by the Society for the Encouragement of Arts (1758–1763), 153
- by Tourville and Hoste (1686), 77, 259–260, 262
- in the Versailles Grand Canal (1681), 68, 74–77, 151
- by Zwijsendregt (1750s), 153–154, 173
- Experimentation, in hydrodynamics
- by Beaufoy (1793–1798), 167, 183, 302
- by Borda (1767), 160–161, 163, 170, 171, 173, 174, 179–180, 182, 244, 287
- by Bossut, Condorcet and D'Alembert (1775), 163–168, 171, 173, 176, 182, 303
- by Du Buat (1779), 164, 167–170, 171, 174, 176, 181, 182
- by Huygens (1668), 126–127, 129, 158
- by Mariotte (1681), 126–127, 129
- by Romme (1783), 164, 170–174, 176, 181, 182
- by Thévenard (1768), 161–164, 173, 176, 182
- use of Pitot's tube in, 168–171
- Extended operations at sea, effect on ship design and technology, 36–37
- Fatio de Duillier, Nicolas, 88, 91, 131–132, 315
- Fausto, Vettor, 47, 298

- Fernández de Landa, José Romero, 25, 30, 180, 244, 293, 315
- Fincham, John and *A History of Naval Architecture* (1851), xii, 23, 78, 179
- Finite elements, early examples in fluid resistance calculations, 134, 136, 141–143
- Fleets Constructors Corps, of Sweden. *See* Naval constructors, Sweden
- Fluid resistance. *See* Resistance of fluids
- Forfait, Pierre, 24, 110, 299
- Fournier, Georges and *Hydrographie* (1643), 48, 195–196, 280–281
- France, naval constructors of. *See* Naval constructors of France
- France, survey of navy, 27–29
- Franklin, Benjamin, 164–165
- Freeboard, early rules for, 195
- French Academy of Sciences. *See* Academy of Sciences Paris
- French East Indies Company, 33, 35 and support of naval architecture, 33, 161–163
- French hydrodynamics
British perceptions of, 176–179
skepticism of, 179–180
- French Revolution, marking the end of the Scientific Revolution, ix, 174, 301–302
- French warships, speed compared with British warships, 176–178
- Friction, in fluid resistance, 150, 163, 167, 168, 170, 175–176
- Froude number, 175–176
- Froude, William, vii, 114, 150, 158, 161, 163, 170, 174, 175, 184, 255, 305
- Furttentbach, Joseph and *Architectura navalis* (1629), xiii, 48
- Galileo Galilei, 159, 195, 262, 298–299
- Gardes de la marine*. *See* Navy Guards, France
- Gautier, Jean-François, 29, 36, 180, 245, 255, 290, 292–293, 315
- Gay, Pierre de, 182–183, 315
- Gazelle* (18-gun), experiments by Bouguer on, 7–8, 227, 232
- Gaztañeta e Iturrizbalzaga, Antonio de, 29, 41
- Génie Maritime*. *See* Naval constructors, France
- Génie Militaire*. *See* Corps of Military Engineers, France
- Geodesic Mission to Peru
Bouguer wounded during, 16
and Bouguer's writing of *Traité du navire* during, 18–20, 135, 263
controversy over results, 17, 233, 307, 308
and the debate over Earth's shape, 8–10, 116, 191
measuring the baseline, 13–15
preparations for, 10–13, 29
return to Europe from, 17–18, 20–22
and triangulation, 14–16
- Gerner, Henrik, 30, 294, 316
- Geslain, Blaise, 139
- Gobert, 139
- Godin, Louis, 9–17, 19, 20–21, 291, 307, 316
- Grand Canal of Versailles. *See* Versailles Grand Canal
- Grandjean de Fouchy, Jean-Paul, 4, 10, 263, 309, 315
- Gravity, theories of, 8–10, 115–117
- Griffiths, John W., 158
- Groignard, Antoine, 33, 239, 253–255, 316
- Guardiamarinas*. *See* Navy Guards, Spain
- Gun ports, effect on ship design, 34–35, 43, 196
- GZ curve, as a measure of stability, 256–257
- Harriot, Thomas, 123
- Hennert, Johann Friedrich, 60, 61n24
- Hermann, Jacob, 95, 133
- Histoire et Mémoire de l'Académie Royale des Sciences de Paris*. *See* Academy of Sciences Paris, publications of
- Hocquart, Jean-Hyacinthe, 203–205, 228, 316
- Hohlenburg, Frantz, 245, 294
- Hoste, Paul, 52, 281, 316. *See also* *Théorie de la construction des vaisseaux* (1697)
and “Architecture navale” (1714), 262
Aristotelian mechanics of, 103, 115, 214

- and *L'Art des Armées Navales* (1697), 87, 100, 260–261
- and maneuvering theory, 87
- model experiments of, 77, 259–260, 262
- and naval tactics, 87, 100, 260–261
- and stability theory (1697), 103, 189, 191, 211–215, 232
- Tourville's influence on, 77, 259–261
- Hudde, Johann van Waveren, 203–204, 248, 316
- Hull model tests. *See* Experimentation, assessment of hull forms; Experimentation, in hydrodynamics
- Huygens, Christiaan, 58, 73, 101–102, 117, 316
- and center of oscillations, 116–117
- and the debate with Renau over the *dérive* (1691–1696), 88–91, 93
- and hydrodynamic experiments (1668), 126–127, 129, 158
- and stability theory (1650), 211
- Hydrodynamics
- experimentation in, 158–173. *See also* Experimentation, in hydrodynamics
- in modern ship resistance theory, 174–176
- theoretical development of, 144–150
- Hydrography schools. *See* Schools of hydrography
- Hydrostatics. *See* Stability; Displacement
- Hyponatremia, first recorded instance (in Renau), 94
- Inclining experiment, 99, 213–214, 232, 242–244, 248, 303
- Industrial Age, ix, xi, 26, 279, 303–305
- Ingénieurs-Constructeurs de la Marine*. *See* Naval constructors, France
- Jefferson, Thomas, 185
- Jesuits
- correspondence as a model for scientific journals, 53, 54
- history of, 51–54
- Jombert (book publishers), 55, 56–57, 263–264, 307
- Journals, scientific, 54–55, 61
- Juan y Santacilia, Jorge, xi, xvii, 316. *See also* *Examen Marítimo* (1771)
- as chief constructor of Spanish navy, 29, 244, 291–292
- and criticism of naval architecture, 23, 25, 180, 244–245, 275, 292
- and espionage in Britain, 29, 272, 273, 291
- hydrodynamic theories of, 180–181
- and maneuvering theory, 98, 275
- and participation in the Geodesic Mission to Peru, 11, 12, 15, 17, 19–22, 29, 244, 272
- and stability, roll and pitch theory, 255–256, 275
- Judichær, Olaus, 199, 294, 316
- Knowles, Charles, 220, 226n89, 269
- Krabbe, Frederick Michael, 245, 294
- Kronan* (124-gun), sinking of, 190
- L'Hôpital, Guillaume-François-Antoine, marquis of, 88, 89, 91, 92, 102, 132–134, 138–139
- La Caille, Nicolas-Louis de, 309–310
- La Condamine, Charles Marie de, 316
- and the Geodesic Mission to Peru, 2, 9–17, 20–22
- and the quarrel with Bouguer, 17, 233, 307–309
- La Croix, César-Marie de, 317
- on the need for weight estimates, 206
- and stability theory (1732–1735), 60, 219–222, 233–237, 266
- La Hire, Philippe de, 89, 91, 127
- Lagrange, Joseph-Louis, 149–150
- Lavanha, João Baptista, xiii, 47
- Le Croisic, 3–6, 106, 204, 307
- Le Monnier, Pierre Charles, 12, 243, 253, 310, 317
- Learned societies. *See* Academies and societies
- Least resistance. *See* Bows of least resistance; Solid of least resistance

- Leibniz, Gottfried, 53, 55, 89, 91, 102, 117, 131–132, 233, 237
- Lévéque, Pierre, 23, 181, 275
- Line of battle, effect on standardization of ship design, 35–36
- Little Navy School, 61, 80, 105, 110, 140, 238, 239, 266, 269–270, 276, 282–286, 289–290, 305, 309
- in the Louvre, 285–286, 307
- Live forces (*vis viva*), 117, 135–136, 145, 146, 161, 167
- Livre tournois*. *See* Money conversion
- Longitude, as major scientific problem, 8, 25, 190
- Louis XIV, 51, 67–69, 77, 89
- Louvre
- as the home of the Academy of Sciences Paris, 58, 286, 307
- as the home of the Little Navy School, 285–286, 307
- Lune* (54-gun), sinking of, 187–188, 213
- MacLaurin, Colin, 95
- Maffioletti, Gianmaria, 32, 299, 317
- Mairan, Jean Jacques d'Ortous de, 5, 103, 104, 194, 203–205, 317
- Maitz de Goimpy, François Louis Edme Gabriel, count of, 60, 61n23, 317
- Maneuvering theory. *See also* *Dérive* of Bouguer (1746–1757), 96, 98–100
- continuation into 19th century, 100–101, 109–110
- of Euler (1749), 97
- of Hoste (1691), 87
- of Juan y Santacilia (1771), 98, 275
- and naval tactics, 96–101
- of Pitot (1727), 95–96
- of Renau, Huygens and Johann Bernoulli (1689–1714), 82–94
- of Savérien (1746), 96
- Marguerie, Jean-Jacques de, 164n129, 317
- Mariotte, Edmé, 78, 81–82, 126–127, 129, 133, 262, 317
- Mary Rose* (37-gun), sinking of, 189–190, 196
- Masting of ships, 102–112. *See also* *Point vélique*; Academy of Sciences Paris, Rouillé de Meslay Prize, Prize on masting (1727)
- Maupertuis, Pierre Louis Moreau de, 9, 12, 59, 97, 146, 288, 307, 317
- Maurepas, Jean-Frédéric Philippe Phélypeaux, count of
- and the Academy of Sciences, 8–9, 58
- biography of, 217–219, 317
- and his support of Bouguer, 6, 7, 28–29, 93, 97, 102, 104, 219, 237, 263, 307–308
- and his support of Duhamel du Monceau, 29, 269, 283–285
- and his support of Geodesic Mission to Peru, 8–12, 217
- and his support of La Croix, 219, 222, 237
- rebuilding the French navy, 28–29, 139, 217
- “Mémoire sur les constructions des vaisseaux” (1679) by Renau, 69–74, 81, 82
- as first known work of naval architecture, 70–71
- Merchant fleets, survey of, 32–33
- Metacenter
- as a science “multiple,” 232–237
- as icon, 187, 295
- calculated in practice, 238–249
- derivation by Bouguer, 7–8, 221, 227–232, 265
- lack of impact on ship design, 249–250, 296
- longitudinal, 256
- used today, x, 7, 187
- Method of trapezoids. *See* Trapezoids, method of
- Michael of Rhodes, 46
- Model tests. *See* Experimentation, assessment of hull forms; Experimentation, in hydrodynamics
- Models. *See* Ship models
- Moivre, Abraham de, 131–132
- Money conversion, xx–xxi
- Monge, Gaspard, 43

- Morineau, Pierre, 272
- Moseley, Henry, 255
- “Multiple” in science
 definition, 233
 the metacenter as, 232–237
- Murray, Mungo, 60, 151–153, 179, 248
- Naval architects. *See* Naval constructors
- Naval architecture. *See also* Ship theory
 definition of, xiii–xvi, 25, 47–48
 dissemination of knowledge of, 59–62
 as a force multiplier, 28, 66, 120–121
 histories of, xi–xiii
 as a means of bureaucratic control of ship
 design, x, 25, 279, 286–287, 303–304
 role in doctrine and technology, 37–38
- Naval constructors
 of Britain, 249, 296–298
 of Denmark, 245, 293–295
 of France, 29, 285–290
 of the Netherlands, 248–249, 298
 of Spain, 245, 290–293
 of Sweden, 187, 246, 295
 of Venice, 298–299
- Naval tactics, 96–97
 and maneuvering theory, 96–101
- Navy Board models. *See* Ship models
- Navy Guards, France, 52, 161, 170, 259, 281
- Navy Guards, Spain, 11, 21, 49, 244, 290–291
- Netherlands VOC (East Indies Company),
 32–33, 35
- Netherlands, naval constructors of. *See* Naval
 constructors, Netherlands
- Netherlands, survey of navy, 31
- Newton, Isaac, 318
 and gravity theories, 8–10, 115–117
 precursors to, 123–127, 138
 Principia (1687) and rational mechanics, 113,
 114, 117, 119
 priority dispute with Leibniz on the
 calculus, 132, 233, 237
 and resistance of fluids, 128–129, 135–136,
 148–149, 160, 163, 167, 168, 174, 184
 and the solid of least resistance, 129–131,
 138–139, 154
- Nystrom, John W., 158
- Ollivier, Blaise, 139, 205–206, 217, 238, 284,
 318
- Oscillations of ships. *See* Roll and pitch
 theory
- Panfilli, Odorico, 140, 303
- Pangalo, Biaggio (Blaise), 74–75, 77, 81
- Parabola method, of Chapman, 158, 278
- Pardies, Ignace Gaston, 69–71, 73, 81–82, 91,
 101–102, 318
- Parent, Antoine, 91, 95, 211, 234, 318
- Pascal, Blaise, ix, 114, 210
- Pendulum, as model of roll for ships, 118,
 251–252, 255, 257
- Pendulums, multiple. *See* Center of oscillation
- Pepys, Samuel, 48, 87, 151, 158, 196–197
- Peru. *See* Geodesic Mission to Peru
- Petit École de Marine*. *See* Little Navy School
- Pett, Peter, 31, 28, 123, 126, 138, 196
- Pett, Phineas, 196
- Petty, William, 57, 123, 126, 138, 151, 197,
 318
- Philosophical Transactions of the Royal Society*.
 See Royal Society
- Picardy Underground Canal, 164–165, 303
- Pitot, Henri de, 318
 and maneuvering theory, 60, 95–96
 and the Pitot tube, 168, 169, 171
- Plans. *See* Ship plans
- Point vélique*. *See also* Masting of ships;
 Academy of Sciences Paris, Rouillé de
 Meslay Prize, Prize on masting (1727)
 Bouguer’s definition of, 104, 106, 216, 265
 controversy over, 108–109
 modern use of term, 109
 practical application of, 108, 110–112,
 137
- Poleni, Giovanni, 41, 99, 121, 151, 249,
 318

- Polhem (Polhammer), Christopher, 49, 214, 318
- Ponts et Chaussées*. *See* Corps of Engineers of Bridges and Roadways
- Principles of Naval Architecture* (1988), vii, xvi, xix, 49, 264
- Professionalization, of naval constructors. *See* Naval constructors
- Publishing books. *See* Book publishing
- Pursuit curves, 97, 99
- Rankine, William, 163
- Ratio of bow resistance, 137, 140–143, 173, 176, 179–180
- Rational fluid mechanics, ship theory in, 120–123. *See also* Hydrodynamics; Experimentation, assessment of hull forms; Experimentation in hydrodynamics
- Rational mechanics, ix, 113–120, 127
- Relaxation method of Chapman, 154–158
- Renau d'Elizagaray, Bernard. *See also* “Mémoire sur les constructions des vaisseaux” (1679); *De la Théorie de la manoeuvre des vaisseaux* (1689)
- in the Battle of Vigo Bay (1702), 92
- biography, 68–69, 94, 318
- captures *Berkeley Castle* (1694), 89
- and Colbert, 28, 51, 68–70
- and the Construction Conferences (1681), 74–78
- death by hyponatremia, 94
- and the *dérive*, debate with Bernoulli (1712–1714), 87, 88, 91, 92–94, 119
- and the *dérive*, debate with Huygens (1691–1696), 88–91, 93
- and the *dérive*, initial ideas of, 71–73
- ellipse theory of ships, 46, 71–74, 78, 79, 80, 88, 133
- as member of Corps of Military Engineers, 81, 92
- mortar-ships of, 78
- and Seignelay, 81–82
- and Vauban, 78, 81, 94
- Republic of Letters, 53, 54, 89
- Resistance of fluids
- pressure theory of, 146–148, 173
- shock theory of, 102, 113, 128–129, 173
- Resistance of ships. *See also* Experimentation, assessment of hull forms; Experimentation, in hydrodynamics; Resistance of fluids
- experimentation on, 151–173
- new ideas in, 180–184
- separation into components, 168–170, 174–175, 183
- using shock theory, 133–143
- Resistance tests. *See* Experimentation, assessment of hull forms; Experimentation, in hydrodynamics
- Retamosa, Julián Martín de, 30, 293
- Reuss's Repetorium* (1801–1821), 121–122
- Reyneau, Charles René, 5, 106, 133–134, 203
- Richelieu, Armand-Jean du Plessis, duke of, 28, 64, 188, 319
- Robins, Benjamin, 158–160, 179, 319
- Roll and pitch theory, 22, 250–256, 275
- Rømer, Ole, 58, 199
- Romme, Nicolas Charles, 60, 164, 170–174, 176, 181–182, 242, 319
- Roquefeuil-Kerlouet, Aymar-Joseph, count of, 160, 243–244, 287, 319
- Rouillé de Meslay Prize. *See* Academy of Sciences Paris, Rouillé de Meslay Prize
- Royal Corps of Naval Constructors (Britain), 207–208
- Royal Katherine* (84-gun), with cono-cuneus hull form, 138
- Royal Louis* (110-gun), inclining experiment on, 239, 303, 310
- Royal Society, 57, 58, 132, 138, 291, 302
- Russell, John Scott, 183–184, 302, 305
- Russian Academy of Sciences. *See* Academy of Sciences Saint Petersburg
- Sail, double tangent rule of, 98, 99, 100–101
- Sails, as curved surfaces, 101–102

- Saint Petersburg Academy of Sciences. *See* Academy of Sciences Saint Petersburg
- Salvini, Andrea, 299
- San Carlo Borromeo* (64-gun), as standard for Venice warships, 41, 99, 101, 249, 299
- Sané, Jacques-Noël, and standardization of ship designs with Borda, 35, 179, 287
- Sauveur, Joseph, 81–82, 319
- Savérien, Alexandre, 96, 108–109, 264, 319
- School of Maritime Engineering, France. *See* Little Navy School
- School of Naval Architecture, Venice, 32, 249, 298–299
- School of Naval Engineering, Netherlands, 298
- School of Paris. *See* Little Navy School
- School of student Engineer-constructors of the Navy. *See* Little Navy School
- School of the Louvre. *See* Little Navy School
- Schools of hydrography, 3, 5, 6, 52, 54
- Schools of Naval Architecture, Britain, 277, 297–298
- Scientia navalis* (1749) by Euler, 56, 57, 59, 97–98, 102, 109, 119, 135–137, 143, 167, 222, 252
- abridged versions of (*Théorie complete de la construction . . .* and *Théorie complète de la construction . . .*), 57, 97, 143, 227, 269, 288
- description of, 266–269
- Scientific revolution
- dating of, ix
- end of, xi, 26, 279, 301–303
- structures of, 51–62
- Seignelay, Jean-Baptiste Colbert, marquis of, 319
- and the Construction Conferences (1681), 74–79
- missions to Britain and Holland, 64
- and the search for a theory of ships, 65–68, 74, 79–80
- shipbuilding regulations of, 65, 66, 79–80
- Seppings, Robert, 254
- 1765 Shipbuilding Ordinance, 29, 210, 239, 245, 286–287, 292, 310. *See also* Choiseul; Duhamel du Monceau; Standardization of ships
- Sewell, John, 176–177, 183, 302. *See also* Society for the Improvement of Naval Architecture
- Sheldon, Charles, 245–246
- Sheldon, Francis (I), 39, 41, 293
- Sheldon, Francis (II), 319
- Sheldon, Gilbert, 59, 214, 246, 320
- Ship
- as compared with an army, 24
- as a composite machine, 24
- Shipbuilding methods, differences in French, Dutch and British, 36, 64, 65, 66, 88, 291–294. *See also* Espionage
- Shipbuilding treatises, 40, 46–49
- Ship models, 38–40, 68, 299
- as a means of bureaucratic control of ship design, 38, 40, 42, 65, 66
- Ship plans, 40–44, 74, 79
- as a means of bureaucratic control of ship design, 38, 42
- mathematics and, 38, 43, 46
- Ship resistance. *See* Resistance of ships. *See also* Resistance of fluids; Experimentation, assessment of hull forms; Experimentation, in hydrodynamics
- Ship theory
- as a force multiplier, 28, 66, 120–121
- as a means of bureaucratic control of ship design, x, 25, 279, 286–287, 303–304
- in rational fluid mechanics, 120–123
- role in doctrine and technology, 37–38
- search by Colbert for, 37, 65–68, 74, 75–80, 82, 120–121
- Shock theory of fluid resistance, 102, 113, 128–129, 173
- Simpson's rule, 246–247, 257, 277
- Simultaneous discoveries. *See* "Multiple" in science
- Smeaton, John, 121, 151, 153, 160, 320

- Society for the Encouragement of Arts, model experiments of, 153, 248
- Society for the Improvement of Naval Architecture, 59, 61, 113–114, 176, 184, 248, 297, 302
- sponsors Beaufoy's experiments, 114, 167, 183, 302
- Solid of least resistance. *See also* Bows of least resistance; Shock theory of fluid resistance as applied to ship design, 133–140, 153, 163
- and the calculus priority dispute between Newton and Leibniz, 132
- early development, 106, 131–133
- Newton's formulation of, 129–131
- persistence of, 184–185
- ships built to the form of, 138–140
- and Thomas Jefferson, 185
- Spain, naval constructors of. *See* Naval constructors, Spain
- Spain, survey of navy, 29–30
- Speed of French warships
- comparison with British warships, 176–178
- contribution of ship theory to, 178–179
- Stability accidents, 187–191
- Stability experiments, 189, 242. *See also* Inclining experiment
- Stability theory
- in the Academy Prize on masting (1727), 214–217
- of Archimedes (220) BC, 207–209
- of Atwood and Vial du Clairbois at large angles of heel (1796–1798), 256–257, 302–303
- of Bouguer (1727), 106, 215, 216
- of Bouguer (1732–1746), 227–237
- of Camus (1727), 105, 215–216
- of Euler (1727), 105, 214–215
- of Euler (1735–1739), 219, 222–227, 233–237
- of Hoste (1697), 103, 189, 191, 211–215, 232
- of Huygens (1650), 211
- of Juan y Santacilia (1771), 256
- of La Croix (1732–1735), 60, 219–222, 233–237, 266
- of Parent (1700), 211
- of Stevin (1608), 209–211
- used by navies in design, 238–239
- Standardization of ships
- arguments against, 36
- by Borda and Sané, 35, 179, 239, 287
- in Britain (Establishments), 31, 35
- in China, 38
- by Colbert, 35, 37–38, 49
- effect on ship design, 25–26, 35–36
- and the line of battle, 35–36
- under the 1765 Shipbuilding Ordinance, 286–287
- in Spain, 36
- in Venice, 31–32, 41, 99
- Stevin, Simon, ix, 114, 115, 118, 195, 209–211, 213
- Stibolt, Ernst Vilhelm, 59, 60, 320
- Stoot, William (Fred), xii
- Strategy. *See* Doctrine
- Stratik (Stratico), Šimun Filin (Simone), 299, 320
- Sutherland, William, 133
- Sweden, Fleets Constructor Corps. *See* Naval constructors, Sweden
- Sweden, survey of navy, 30
- Swedish Academy of Sciences. *See* Academy of Sciences Sweden
- Tactics. *See* Doctrine; Naval tactics
- Technology, effect on ship design, 33–37
- Théorie de la construction des vaisseaux* (1697)
- by Hoste, 48, 87, 91, 133, 189, 211, 213
- description of, 259–262
- Thévenard, Antoine-Jean Marie, 33, 110, 163–164, 320
- Thurah, Diderich Lauritsen de, 199, 300
- Tonello, Gasapard, 158, 299
- Tourville, Anne-Hilarion de Cotentin, count of, 320

- and the Construction Conferences (1681), 74–78
- influence on Hoste, 77, 87, 96, 259–261
- influence on Renau, 74–75, 77
- Tractat om Skepps-Byggeriet* (1775) by Chapman, 60, 154, 246, 295
- description of, 275–278
- Simpson's rule in, 246–247
- Traité du navire* (1746) by Bouguer, 48, 97, 98, 102, 108, 135–137, 222, 227, 251
- as central thread in the history of naval architecture, x, 1
- “De la Mâtüre des vaisseaux” (1727) as predecessor to, 108
- description of, 262–266
- duplicate copy of manuscript, 19–20
- illustrations in, 42, 57
- price of, 55
- as principal text in the Little Navy School, 284
- writing of, 1, 7, 18–20, 262–264, 307, 309
- Trapezoids, method of, 203–205, 228, 265
- Triton* (60-gun), masting experiments on, 108
- Triton* (slave ship), Bouguer's return from Peru on, 22, 252, 307
- Tunnage rules. *See* Admeasurement
- Turgot, Anne-Robert-Jacques, 164, 269, 320
- Udemans Junior, Willem, 33, 49
- Ulloa y de Torre-Guiral, Antonio de, xi, 11, 12, 15, 17, 20–21, 29, 291, 321
- Varignon, Pierre, 119, 133, 203–205, 228, 321
- Vasa* (64-gun)
- sinking of, 30, 189, 190
- stability experiment on, 189, 242
- Vauban, Sébastien Le Prestre, marshal of, 77–78, 92, 94, 279–280, 321
- Vector composition of forces, 69–70, 93–94, 118–119
- Venice
- Arsenal of, 31–32, 67, 249, 298–299
- School of Naval Architecture (*see* School of Naval Architecture, Venice)
- survey of navy, 31–32
- Verenigde Oostindische Compagnie* (VOC). *See* Netherlands VOC
- Verne, Jules, 113
- Versailles Grand Canal
- construction of, 67–68
- fleet of, 68, 76
- model experiments in (1681), 74–77, 151
- Vial du Clairbois, Honoré-Sébastien, 60, 256–257, 276, 290, 298, 302, 321
- Victory* (104-gun), model experiments (1937), 175
- Vinci, Leonardo da, 150
- Virtual displacements and virtual velocities, 103, 114–115
- Vis viva*. *See* Live forces
- VOC (*Verenigde Oostindische Compagnie*). *See* Netherlands VOC
- Voltaire (François Marie Arouet), 11, 12, 53, 91, 139, 308
- Vortices or attraction, as theories of gravity, 8, 115–117
- Wallis, John, 75, 123, 126, 127, 136, 138, 321. *See also* Cono-cuneus
- Waveline principle, of John Scott Russell, 184
- Wegersløff, Frederik, 222, 245, 294
- Weight estimates
- development of, 205–207
- faulty, 242
- tabulation by group, 206, 239
- Whole-moulding, 40
- Witsen, Nicolaes, 48, 203, 321
- Zwijndregt, Pieter Pauluszoon van, 33, 153–154, 173, 321

